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ASTP SIMULATED LIGHTNING TEST REPORT

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ASTP SIMULATED LIGHTNING TEST REPORT

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1.0 PURPOSE

The planned date for launching the Apollo Soyuz Test Project (ASTP) spacecraft occurs during the summer, which is the period of peak lightning activity at the launch site. A simulated lightning test was therefore conducted on the backup spacecraft for the ASTP mission (CSM-119) to determine the susceptibility of the Apollo spacecraft to damage from the indirect effects of lightning. Direct lightning effects were not considered. The test had two objectives. The principal objective was to determine if critical spacecraft circuits could survive a full-threat lightning stroke (200 000 amperes peak in 2 microseconds); however, to do this, another objective had to be satisfied. Previous test programs and recent analytical work indicated that induced lightning effects from low-level injected currents could be scaled linearly to those which would be obtained in a full-threat lightning stroke. The second objective was to verify the accuracy of linear scaling.

2.0 TEST APPROACH

The spacecraft was subjected to simulated lightning current pulses having the same rise and fall times of full-threat natural lightning, but with reduced amplitudes of 4000 and 8000 amperes peak (1/50th and 1/25th of a full-threat lightning stroke).

Selected critical circuits were monitored using special instrumentation. Pass/fail criteria were based on analyses and electrical component maximum d-c ratings. The test data were used in conjunction with the pass/fail criteria to determine if monitored circuits can survive natural lightning.

Testing to determine lightning effects on pyrotechnic circuits was conducted with the spacecraft powered down. Testing to determine lightning effects on all other spacecraft circuits was conducted with the spacecraft powered up in the ascent mode.

Oscilloscope data were obtained on five spacecraft circuits during the powered-down testing. In addition, the 78 pyrotechnic circuits were monitored with special devices.

Twenty-three critical circuits were measured with the spacecraft systems powered up.

3.0 TEST DESCRIPTION

3.1 Test Configuration

3.1.1 Test article.- The test article was spacecraft CSM-119 with systems configured for flight except as follows:

a. The solid propellants were removed from the launch escape system, but the flight electrical harnesses were installed.

b. Two 400-ampere-hour batteries were used in lieu of the fuel cells.

c. The Applications Technology Satellite communication equipment was not installed.

d. The experiments were not installed.

e. The augmented television was not installed.

f. The video tape recorder was removed.

g. The command module boost protective cover was removed.

h. The propulsion system pressure/temperature sensors were disconnected.

i. Parachutes and associated deployment mortars were removed.

3.1.2 Configurations for powered-up and powered-down modes.- For the powered-up tests, the configuration included all spacecraft systems that would normally be powered up in the ascent phase of flight except for the following:

a. Service propulsion system gimbal motors

b. Cryogenic heaters for the service propulsion and reaction control systems

c. Television

d. Optics

e. Experiments

f. Environmental control system secondary coolant loop

g. Communications system S-band power amplifier

h. Fuel cells

The spacecraft systems were monitored via telemetry for proper operation.

In the powered-down test mode used for the pyrotechnic circuits, the fuel cells were disconnected and replaced with a fused short. Stray electrical energy indicators (SEEI's) were installed in 78 locations on the spacecraft. The SEEI bodies were connected to spacecraft structure through individual grounding straps. All installed flight pyrotechnics were left in place with Faraday caps installed.

3.1.3 Special equipment.- The simulated lightning current was generated and delivered to CSM-119 by the surge generator and coaxial feed system shown in figures 1 and 2. The coaxial feed system minimized the total inductance of the circuit and permitted maximum rate-of-change of current to be delivered. In addition, the coaxial feed system produced a spacecraft current distribution similar to that which would occur from a natural lightning stroke.

Induced voltages were measured using eight Tektronix type-475 oscilloscopes with measurement cable/attenuators. Polaroid cameras were used to record the data. The oscilloscopes were battery powered and shielded in screen boxes for maximum isolation from the magnetic fields caused by the simulated lightning current (fig. 3). The oscilloscopes were triggered optically from the lightning generator by the use of fiber optics. Each of the measurement cables consisted of a twisted-shielded pair with an additional overall shield grounded to the screen box. The measurement cables included built-in isolation resistors and attenuators that maintained continuity of the spacecraft circuits while providing inputs to the oscilloscopes.

Two special measurement coils were mounted in the command module tunnel. The effective area of each coil was 0.155 square meter, and the measurement system was configured to measure the open circuit voltage and the short circuit current for each coil.

3.2 Critical Circuit Selection

3.2.1 Field level prediction.- The main lightning current paths in the spacecraft structure are easily identified. Current division among the various paths cannot, however, be easily determined. Therefore, current was assumed to be distributed in a manner that would give the worst-case predicted fields. Table I gives the rate-of-change of flux density for different spacecraft zones based on the following considerations.

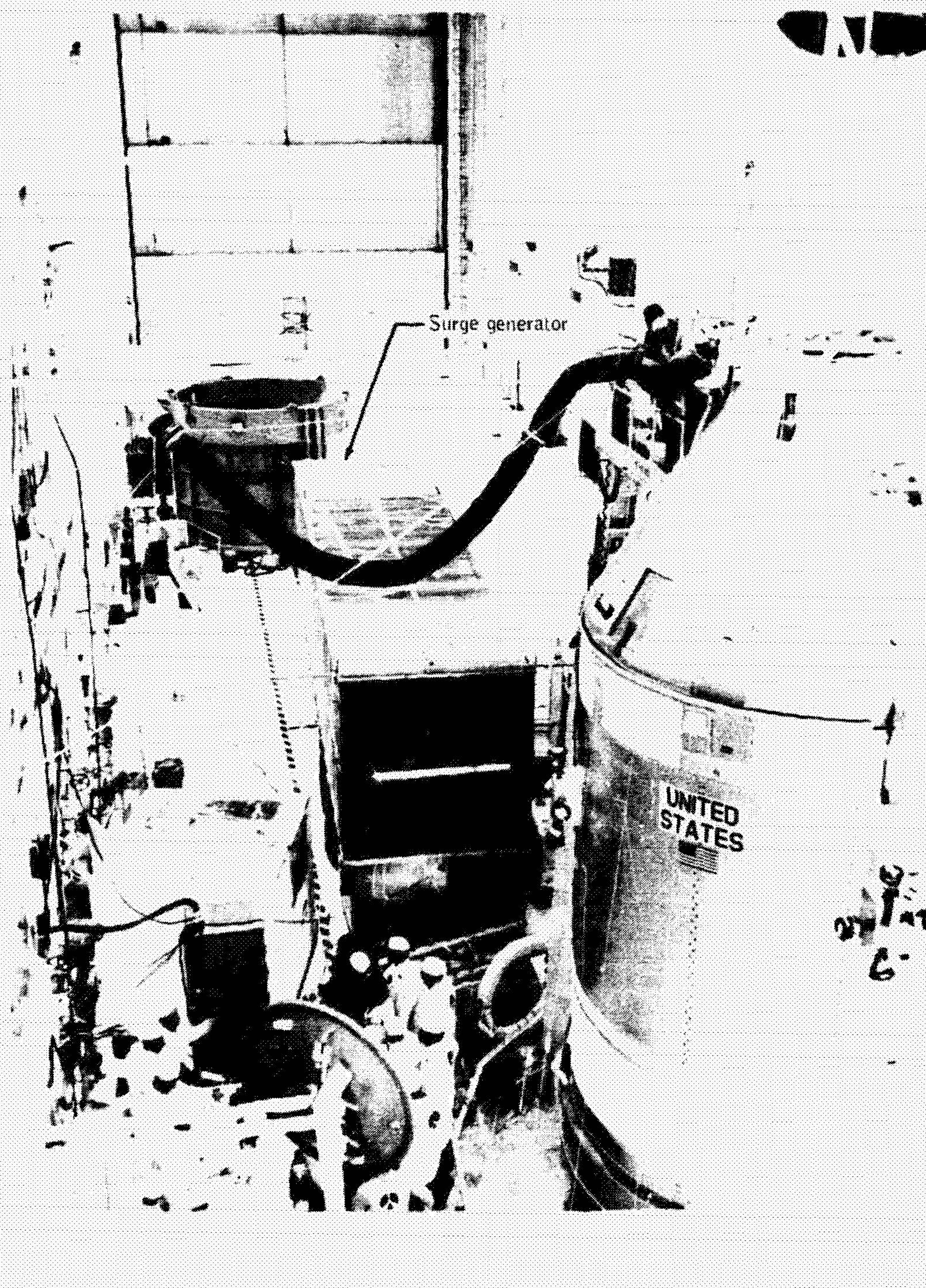


Figure 1.- Test setup for generation and delivery of simulated lightning.

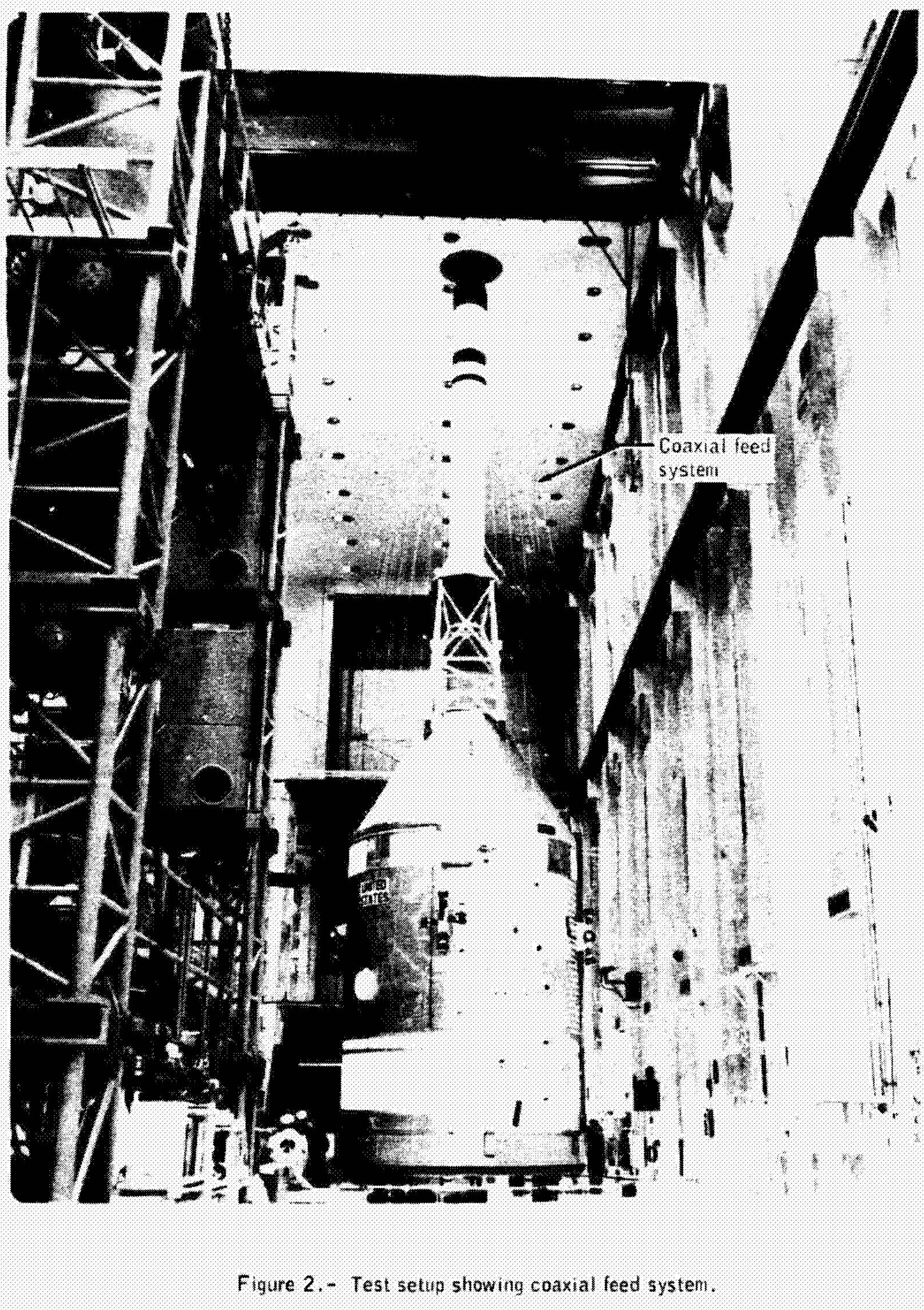


Figure 2.- Test setup showing coaxial feed system.

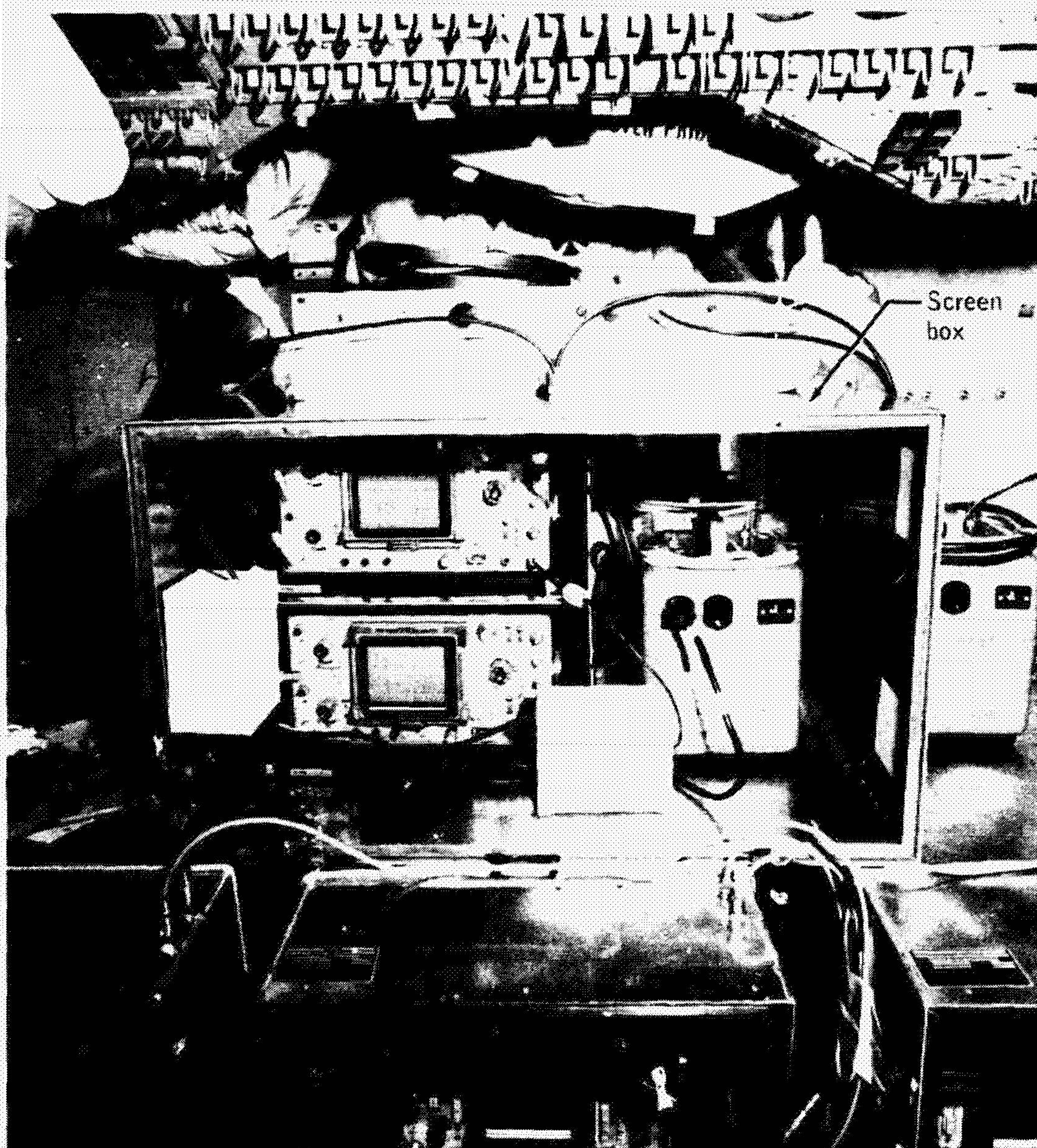


Figure 3.- Installation of oscilloscopes in command module.

TABLE I.- FIELD RATE OF CHANGE IN SPACECRAFT ZONES

Zone	Flux density rate-of-change, Wb/m^2sec
Service module bays	16 000
Service module upper deck	20 000
Command module/service module umbilical	200 000
Command module cabin	1 600
Command module inner-to-outer shell	6 700

a. Service module bays - The cylindrical service module contains six internal longitudinal plates and a central cylindrical core. One edge of each plate is fastened to the central core. The other edge is fastened to the inner surface of the outer skin. The inductance of each plate in the longitudinal direction is about one-sixth of the inductance of the outer shell. Each plate was, therefore, assumed to conduct one-twelfth of the lightning current. Analysis showed that a lightning current rate-of-change of 100 000 amperes per microsecond would cause a flux density rate-of-change of 16 000 Wb/m^2sec near the plate.

b. Service module upper deck - Four primary current paths exist between the command module and the service module. Three of the paths are the three metallic tension ties and the fourth is the umbilical plumbing. For analysis purposes, all lightning current was assumed to flow down the center line of the vehicle in order to compute the fields in the service module upper deck. The total resulting magnetic flux over the upper deck was then calculated and averaged to give an upper deck flux density rate-of-change of 20 000 Wb/m^2sec.

c. Command module/service module umbilical - The command module/service module umbilical represents a special case in that all wiring between the two modules runs through the umbilical. The worst-case assumption that all of the lightning current would flow through the umbilical gave a flux density rate-of-change of 200 000 Wb/m^2sec.

d. Command module cabin - The command module consists of two metal shells, one inside of the other. The inner shell is the pressure vessel that contains the cabin. Command module cabin fields were assumed to result only from aperture coupling through the windows. This gave a calculated field rate-of-change of 1600 Wb/m^2sec.

e. Command module inner-to-outer shell - Wiring to the service module, the command module reaction control system, and the command module pyrotechnics is routed in the space between the two shells. One-half of the lightning current was assumed to flow down the inner shell, which gave a field rate-of-change of 6700 Wb/m^2sec.

3.2.2 Induced voltage prediction.- Spacecraft electrical and electronic systems are grounded to structure at a single-point located in the command module cabin. Induction is the primary mode of voltage coupling from lightning currents into the spacecraft wiring. The induced voltage is equal to the time rate-of-change of the flux that links the supply and return wires in the circuit under consideration. The time rate-of-change of flux linkage is equal to the flux density rate-of-change multiplied by the effective area between the supply and return wires. Table II gives effective loop areas for various wire types.

TABLE II.- EFFECTIVE LOOP AREAS FOR VARIOUS TYPES OF WIRING

Type	Area/1-meter length, sq m
Twisted pair	30×10^{-6}
Shielded twisted pair	30×10^{-7}
Nontwisted pair	25×10^{-3}
[a]Any wire to structure	50×10^{-3}

[a]Common mode.

3.2.3 Monitor point selection.- Voltages induced in spacecraft wiring were calculated using wire type, length, and routing with the predicted fields. Terminating circuitry was then analyzed to identify those circuits in which the component maximum d-c ratings were exceeded by the calculated induced voltages.

Many spacecraft systems repetatively use circuits that are identical except for wire routing. For example, all reaction control system engine valve drivers are the same. In such cases, the circuit that would be subjected to the highest predicted induced voltage was monitored.

The analyses identified too many candidate circuits for a manageable test. Consequently, the most sensitive flight-critical circuits were monitored.

3.3 Pyrotechnic Initiator Substitution

Calculations showed that the induction would couple insufficient energy into pyrotechnic circuits to fire the initiators in the pin-to-pin mode, but they indicated that common-mode voltages might be high enough to exceed pin-to-case acceptance test level of the initiators.

Pin-to-case spark gaps are built into each of the single bridgewire Apollo standard initiators (SBASI) that are used for flight. The spark gaps are designed to fire between 1000 and 1400 volts and should limit the bridgewire-to-case voltage to that level, regardless of what voltage is applied pin-to-case. Each initiator is tested with a pin-to-case pulse of 25 000 volts to screen for quality defects; however, approximately 0.1 percent of the units passing this test fail if resubjected to the same test. (Additional testing is planned to determine why this occurs.) An all-fire level of 25 000 volts was therefore assumed for the flight initiators.

Reduced-level lightning tests were used to avoid damage to the flight vehicle test article and remain within the capability of the lightning generator. Because the test levels were subscale, a go/no-go device was used to simulate the SBASI. This simulator, discussed in appendix A, is called a stray electrical energy indicator (SEEI), and was originally developed for use in radio-frequency sensitivity tests. Table III presents the results of testing 12 SEEI units from the lot shipped to KSC for the simulated lightning test.

TABLE III.- STRAY ELECTRICAL ENERGY INDICATOR FIRE AND NO-FIRE LEVELS

Fire, volts	No-fire, volts
1000	600
750	575
625	575
625	550
600	500
575	500

Each SEEI was subjected to a single discharge from a 500 picofarad capacitor at the test voltage indicated. Based on these results, an all-fire level of 750 volts was chosen. The SEEI/SBASI ratio of sensitivity was therefore established at 750/25 000 or 1/33.

A full-threat natural lightning stroke reaches a peak current of 200 000 amperes in 2 microseconds. An average stroke reaches 30 000 amperes in 2 microseconds. Using a device sensitivity scale factor of 33:1, the test levels shown in table IV were planned in order to demonstrate a 6-decibel safety margin.

TABLE IV.- PLANNED PYROTECHNIC TEST LEVELS

Planned test level, amperes (a)	Margin of safety			
	30 000-ampere stroke (a)		200 000-ampere stroke (a)	
	Ratio	dB	Ratio	dB
4 000	4/1	+12	0.66/1	-3.6
8 000	8/1	+18	1.32/1	+2.4
12 000	12/1	+21.5	2/1	+6

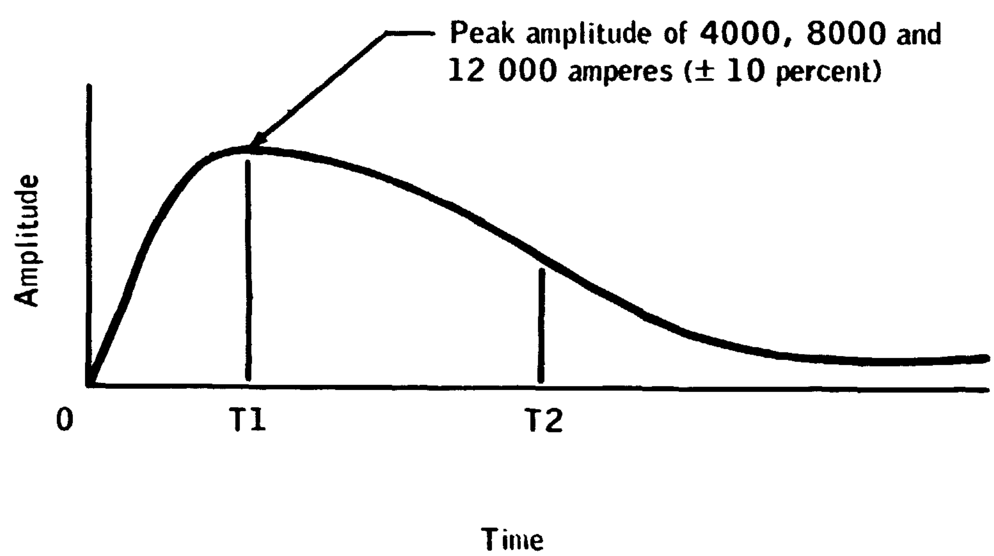
[a]Time to peak was 2 microseconds in all cases.

3.4 Test Conditions

3.4.1 Generation of simulated lightning current.- The simulated lightning current waveform (fig. 4) specified in the test plan was selected to duplicate the frequency spectrum of natural lightning. Peak currents of 4000, 8000, and 12 000 amperes were selected to verify pyrotechnic circuit margins.

An equivalent circuit of the surge generator and test vehicle is shown in figure 5. The total inductance (L) of the generator, feed wiring, and vehicle under test was predicted to be in the 6- to 10-microhenry range. The total inductance of the system was measured to determine the charge voltage to be used on the capacitor bank to achieve a given peak current. This was done by removing the damping resistor (R) from the circuit, discharging the 6-microfarad capacitor (C) through the system inductance, and observing the natural frequency of the system. Under these conditions:

$$L = \frac{1}{4\pi^2 f^2 C}$$



T1 (time to peak value) = 2 microseconds (± 1 microsecond)
T2 (time to half-value) = 50 microseconds (± 25 microseconds)

Figure 4.- Test waveform.

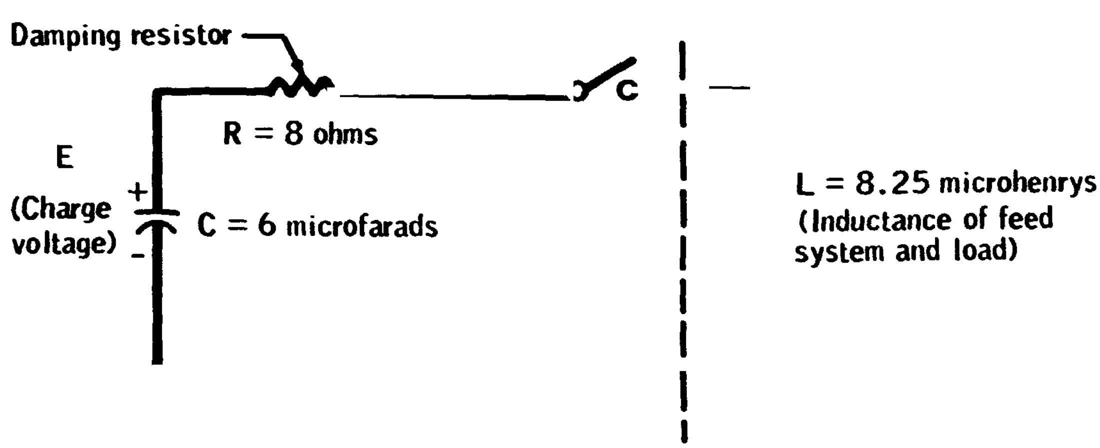


Figure 5.- Equivalent circuit of lightning current generator and load.

The frequency of the response is shown on the oscillogram in figure 6. The natural frequency was 22.6 kilohertz and the system inductance was determined to be 8.25×10^{-6} henrys.

To achieve the specified waveform with a 4000-ampere peak current the following conditions had to be met:

(1) $I_{peak} \times R = E$, and $\frac{dI}{dt} = 0$

when $t = 2$ microseconds.

(2) $\frac{dI}{dt}_{average} = 2000$ amperes/microsecond during rise.

(3) $RC \simeq T_2 - T_1 = 48$ microseconds.

The rate-of-change of current at time zero is approximately twice the average rate-of-change of the waveform during the first 2 microseconds. Therefore, the rate of current change at the time of switch closure is 4000 amperes per microsecond. The capacitor bank charge voltage is then given by equation 4:

(4) $E = L \frac{dI}{dt} = (8.25 \times 10^{-6})\ (4 \times 10^{9}) = 33 \times 10^{3}$ volts

when $t = 0$

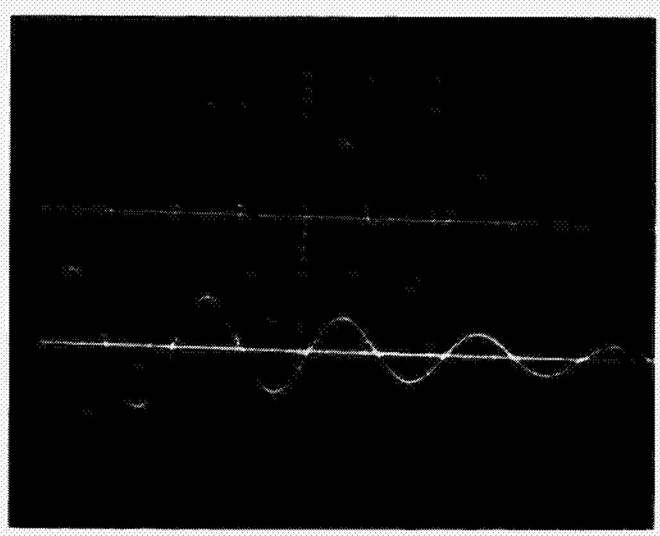
The value of R is selected such that equation 1 is satisfied:

(5) $R \simeq \frac{E}{I_{peak}} = 8.25$ ohms

where $E \simeq 33 \times 10^{3}$ volts at $t = 2$ microseconds.

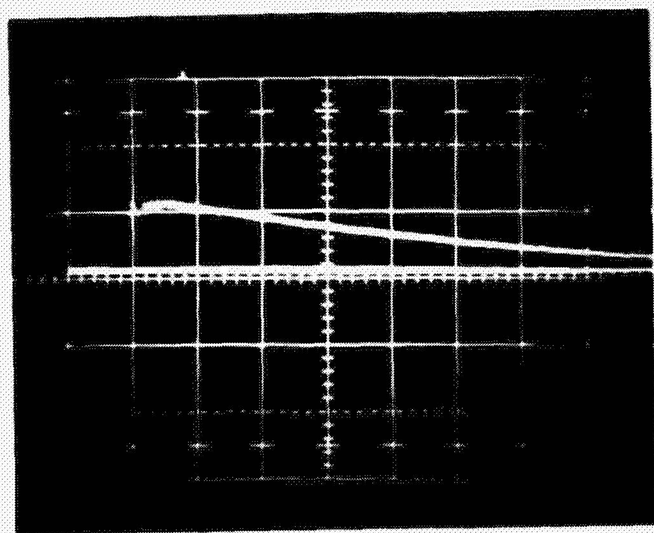
The time for the current to decay to 63 percent of its peak value is determined by the RC time constant (equation 3) which is 48 microseconds.

The current waveforms delivered to the vehicle are shown in figure 7 for the 4000- and 8000-ampere peak currents, respectively. The current was monitored for each strike using a 1-meter-diameter $\frac{dI}{dt}$ coil

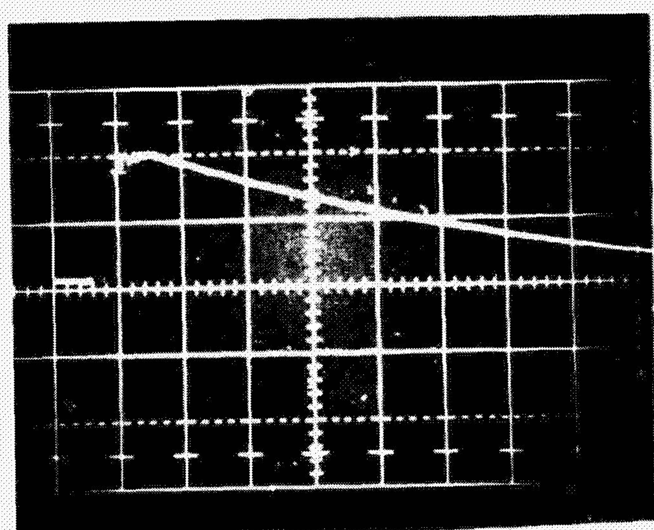


Vertical: Channel 1 = 0.1 volt/division
Channel 2 = 5 volts/division
Sweep speed: 20 microseconds/division

Figure 6.- Natural frequency of lightning generator, feed system and vehicle under test.



Test pulse: 4000 amperes in 2 microseconds
Vertical: 0.2 volt/division
Sweep speed: 5 microseconds/division
Scaling factor: 1 volt = 21 000 amperes



Test pulse: 8000 amperes in 2 microseconds
Vertical: 0.2 volts/division
Sweep speed: 5 microseconds/division
Scaling factor: 1 volt = 21 000 amperes

Figure 7.- Waveforms obtained with 4000- and 8000-ampere pulses.

(fig. 8) feeding a passive integrator and an oscilloscope with camera. The current waveform and peak current were repeatable and well within specification values. Further reference to current waveforms and peak current values in this report will refer to the specification value unless otherwise noted.

The test 4000-ampere peak current waveform has an average $\frac{dI}{dt}$ during the current rise of 2000 amperes per microsecond. The full-threat lightning stroke has a 200 000-ampere peak and an average $\frac{dI}{dt}$ during the current rise of 100 000 amperes per microsecond. Voltages and currents induced into the vehicle circuitry by the 4000-ampere-peak test waveform, therefore, represent 1/50th of full-threat lightning induction.

3.4.2 Induced voltage measurements.- A schematic diagram of the measurement cable and its connections to the oscilloscope is shown in figure 9. Measurements were made on oscilloscope inputs A and B with respect to ground. The oscilloscope input channels were set to be summed (A + B mode) or to be subtracted (A - B mode). In the A + B mode, the vertical deflection of the oscilloscope was proportional to one-half the sum of $V_1 + V_2$, the average common mode voltage. When the oscilloscope was set to the A - B mode, the vertical defelection was proportional to $V_1 - V_2$, the differential or line-to-line voltage. The maximum common-mode voltage, then was proportional to the average common-mode voltage plus one-half of the differential voltage. Thus, the oscilloscope could be operated in either of two imput modes, allowing a line-to-line or a line-to-ground measurement to be made without a change of connection points for the test cable.

The 5000-ohm series resistors in each measurement line prevented capacitance loading of the signal source by the distributed capacitance of the measurement cable. The terminating resistor at the oscilloscope input in conjunction with the 5000-ohm series resistors provided an attenuation of the measured signal that prevented oscilloscope saturation. In addition, the terminating resistors were chosen to match the surge impedance of the measurement cable.

The voltages developed at oscilloscope inputs A and B are derived in equations 6 and 7 when the loading effect of the 5000-ohm resistors is neglected. This simplification introduces less than 2 percent error.

$$(6) \quad V_A = \frac{75}{5000} \times V_1 + \frac{1}{3} \times \frac{75}{5000} \times V_2$$

$$(7) \quad V_B = \frac{75}{5000} \times V_2 + \frac{1}{3} \times \frac{75}{5000} \times V_1$$

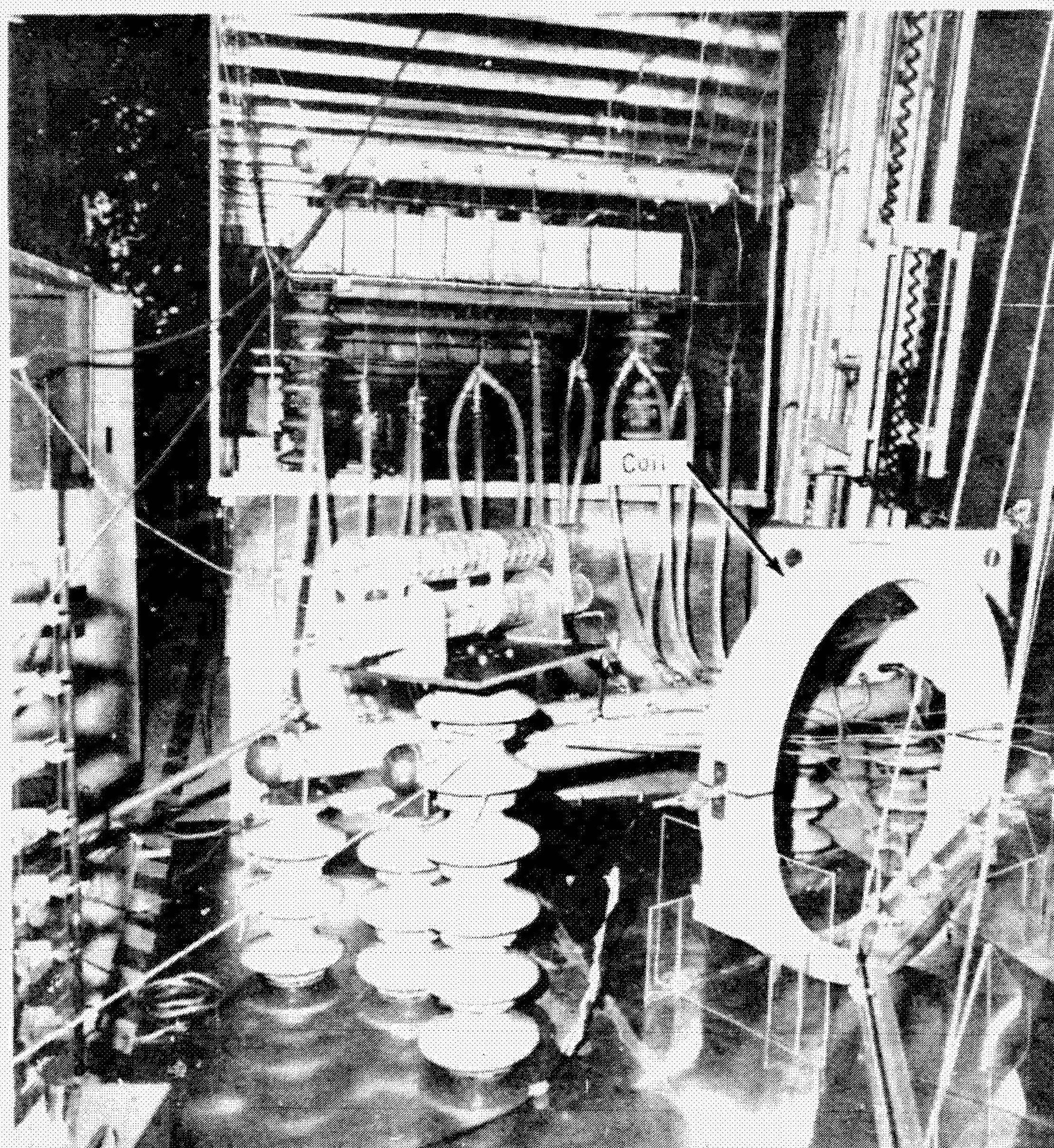


Figure 8.- One-meter-diameter coil feeding passive integrator and oscilloscope.

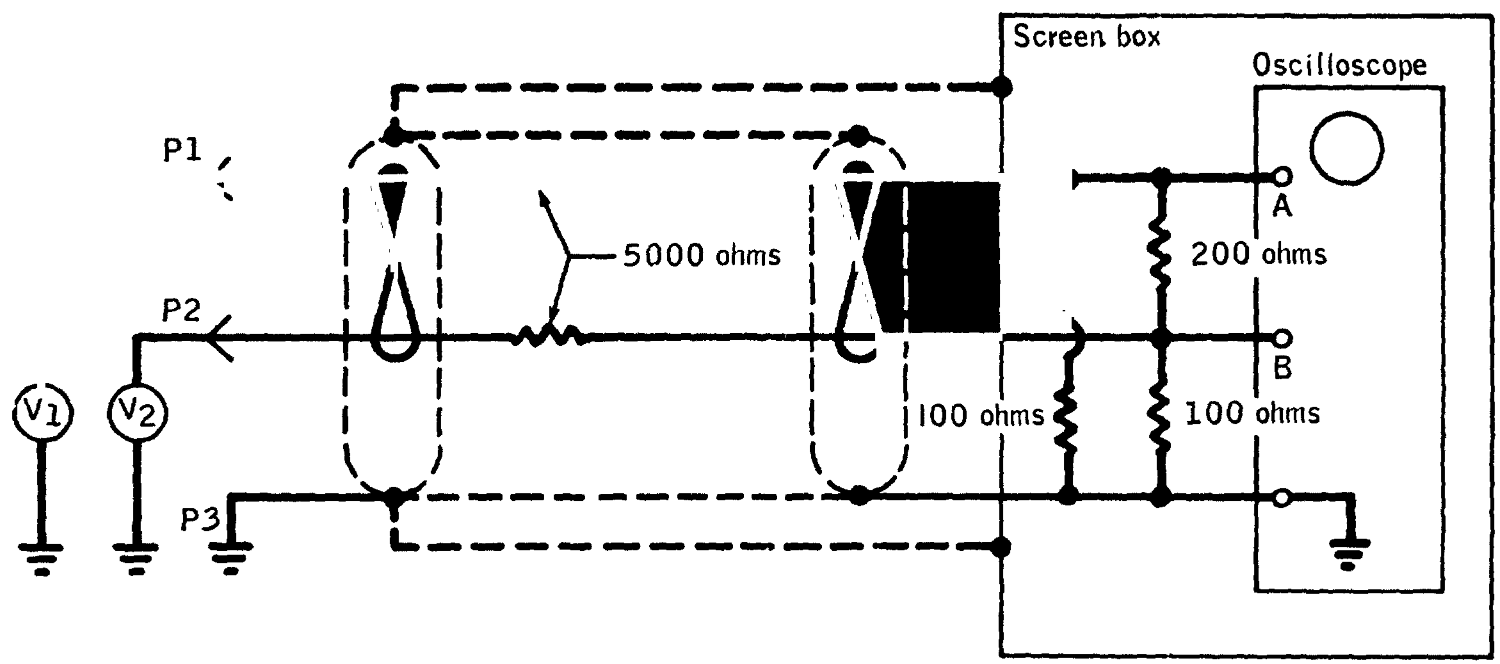


Figure 9.- Instrument cable and oscilloscope connections.

Vertical deflection of the oscilloscope in the A + B mode is obtained by the addition of equations 6 and 7 and results in equation 8.

$$(8) \quad V_A + V_B = V_1 \times \frac{100}{5000} + V_2 \times \frac{100}{5000} = \frac{1}{50} (V_1 + V_2)$$

Vertical deflection of the oscilloscope in the A - B mode is obtained by subtracting equation 7 from equation 6 and results in equation 9.

$$(9) \quad V_A - V_B = \frac{50}{5000} \times V_1 - \frac{50}{5000} \times V_2 = \frac{1}{100} (V_1 - V_2)$$

Based on equations 8 and 9, the vertical oscilloscope deflection in volts should be multiplied by 100 to obtain the line-to-line voltage ($V_1 - V_2$). Vertical deflection should be multiplied by 50 to obtain the sum of line-to-ground voltages ($V_1 + V_2$).

The stated vertical deflections of all oscillograms in this report have been corrected to remove the attenuation factors and reflect actual measured induction.

4.0 TEST RESULTS

4.1 Linearity of Scaling

Analytical work and previous tests indicate that induced voltages resulting from low-amplitude test currents can be scaled up to full-threat lightning levels. One of the objectives of this test was to verify the linearity of scaling.

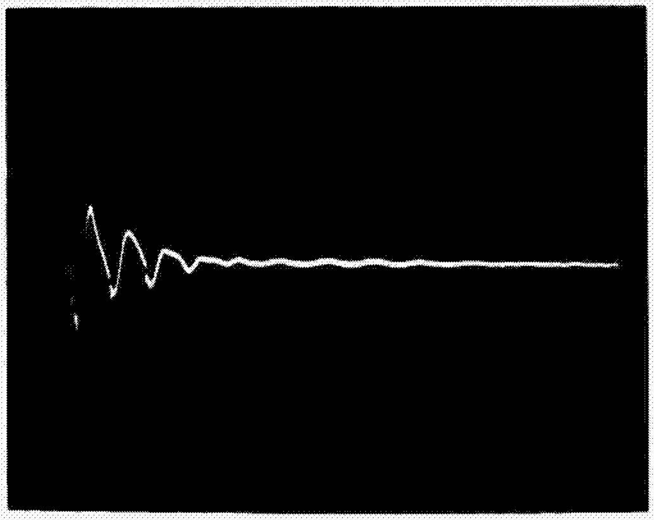
Table V shows the relative induced voltage measured at the 4000- and 8000-ampere stroke levels. The two values for each circuit were multiplied by a constant that was selected to normalize the value measured at 8000 amperes at 200 volts. When all values were averaged, the voltage at the 4000-ampere stroke level was 18.2 percent higher than the linear predicted value.

Figures 10 through 15 are six sets of oscillograms taken at the 4000-ampere and 8000-ampere stroke levels. Examination of the oscillograms shows that in cases where the induced voltage was dominated by high frequency content, the peak amplitude at the 8000-ampere stroke level was less than two times that resulting from the 4000-ampere stroke.

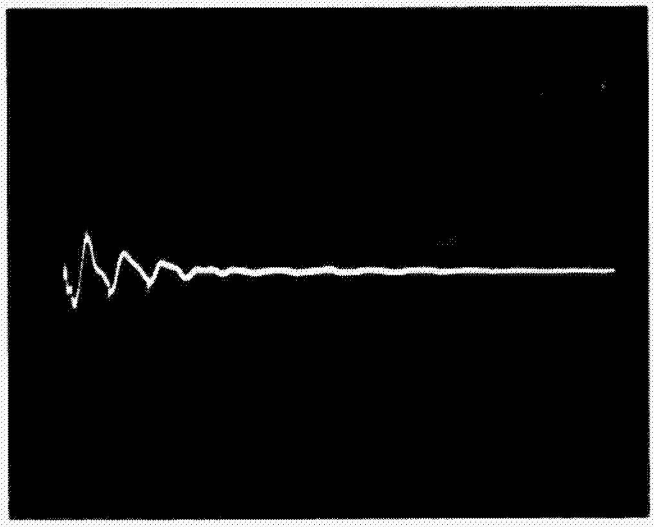
TABLE V.- NORMALIZED INDUCED VOLTAGES MEASURED AT 4000- AND 8000-AMPERE STROKE LEVELS

Circuit	Induced voltage, volts		Error at 4000-ampere level, percent
	4000-ampere stroke pulse (a)	8000-ampere stroke pulse (a)	
DC bus main A	132	200	+32
Coupling data unit to structure	104	200	+4
AC bus 1, phase A (A - B)	82.5	200	-17.5
AC bus 2, phase A (A - B)	100	200	0
AC bus 1, phase A (A + B)	138	200	+38
AC bus 2, phase A (A + B)	153	200	+53
Average total:	118.2	200	+18.2

[a] Time to peak was 2 microseconds.

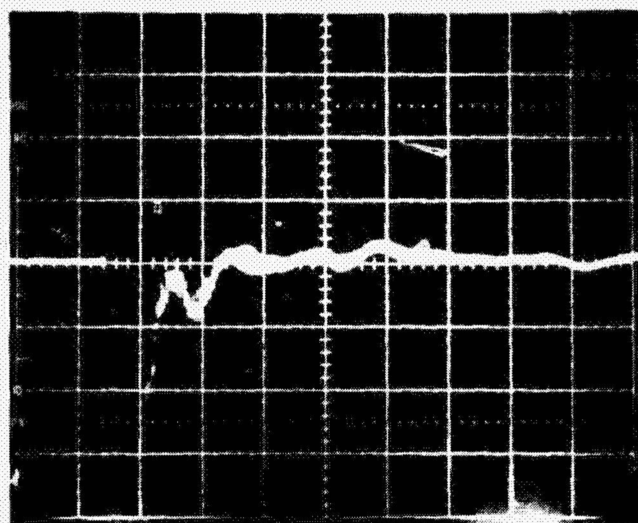


Test pulse: 4000 amperes in 2 microseconds
Vertical: 2 volts/division
Sweep speed: 50 microseconds/division
Measurement mode: A - B

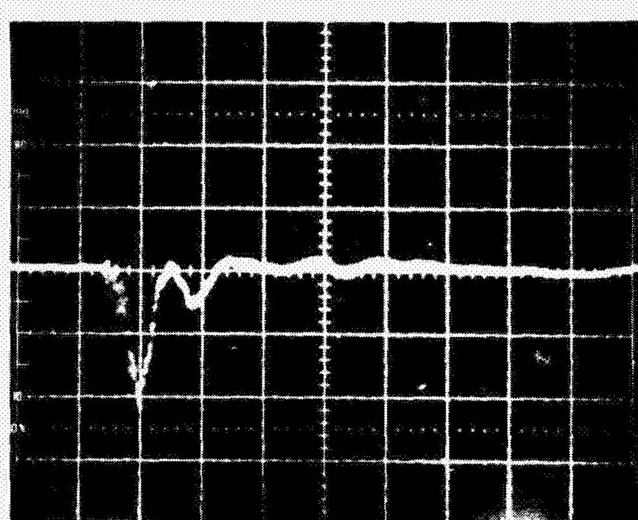


Test pulse: 8000 amperes in 2 microseconds
Vertical: 5 volts/division
Sweep speed: 50 microseconds/division
Measurement mode: A - B

Figure 10.- Induced voltage, d-c bus main A.

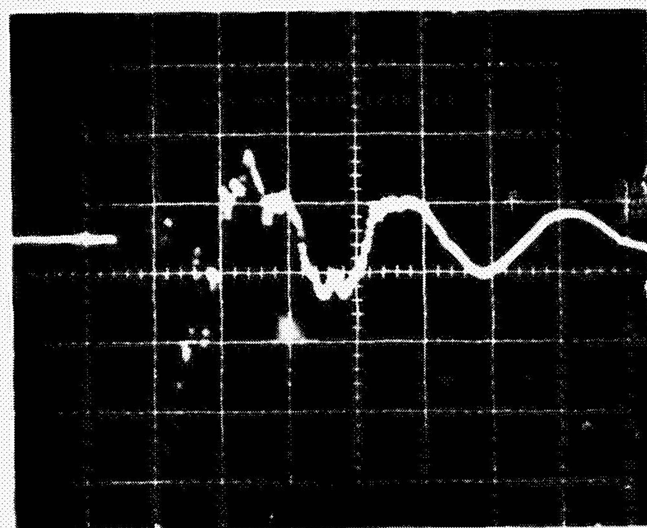


Test pulse: 4000 amperes in 2 microseconds
Vertical: 10 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

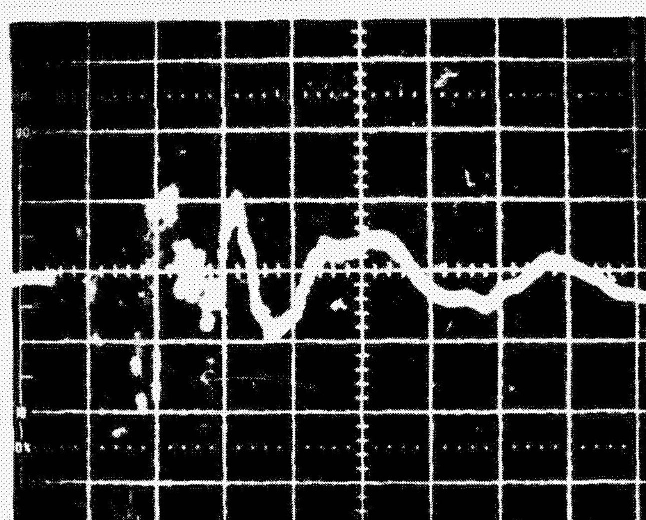


Test pulse: 8000 amperes in 2 microseconds
Vertical: 25 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

Figure 11.- Induced voltage, coupling data unit to structure.

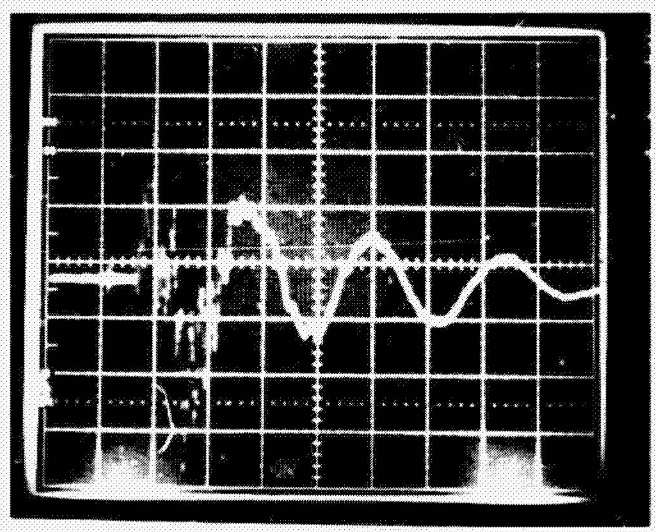


Test pulse: 4000 amperes in 2 microseconds
Vertical: 5 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B

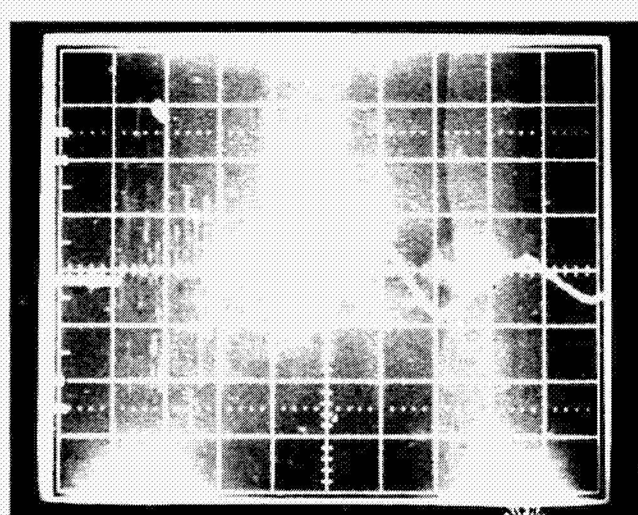


Test pulse: 8000 amperes in 2 microseconds
Vertical: 10 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B

Figure 12.- Induced voltage, a-c power bus 1, phase A (input mode: A - B).

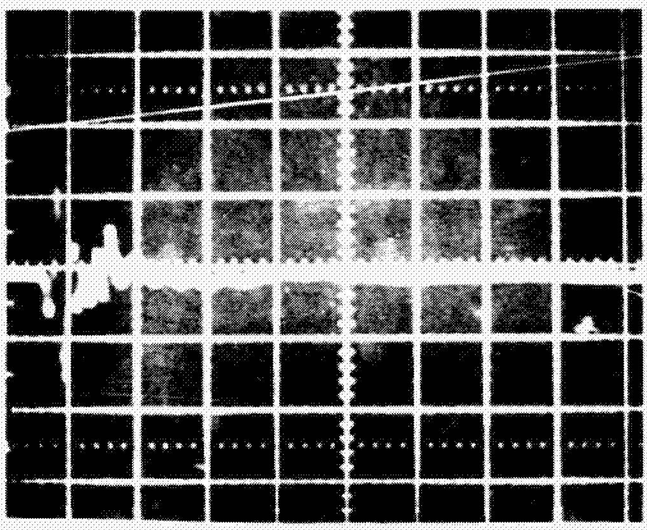


Test pulse: 4000 amperes in 2 microseconds
Vertical: 5 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B

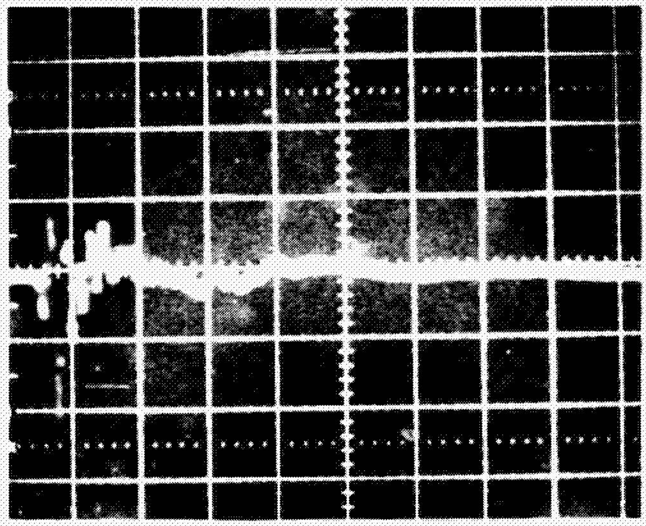


Test pulse: 8000 amperes in 2 microseconds
Vertical: 10 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B

Figure 13.- Induced voltage, a-c power bus 2, phase A
(input mode: A - B)

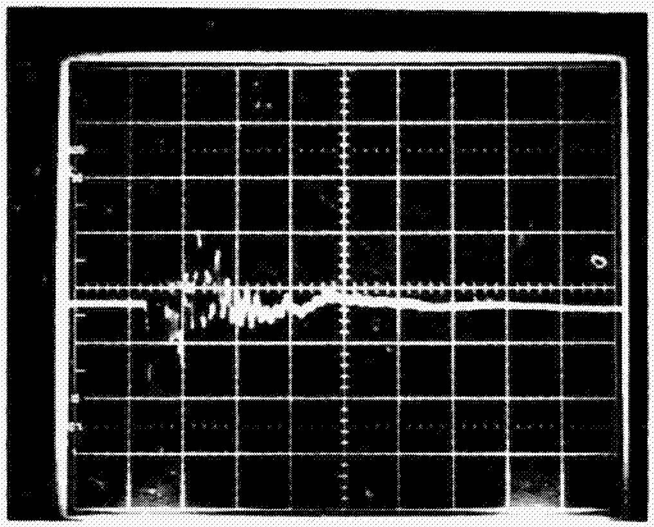


Test pulse: 4000 amperes in 2 microseconds
Vertical: 100 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

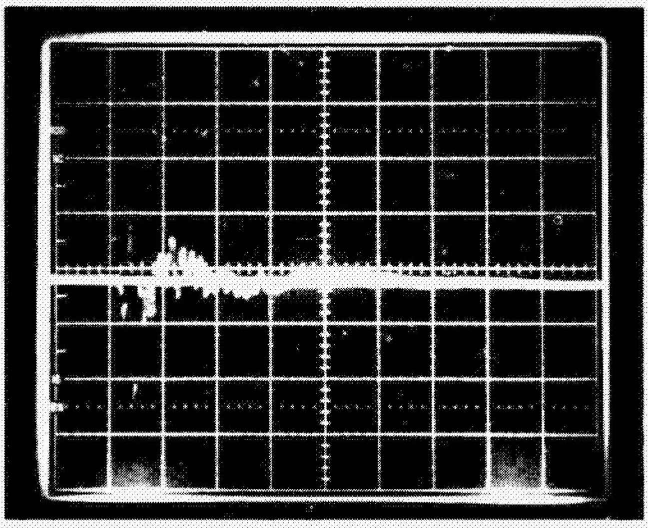


Test pulse: 8000 amperes in 2 microseconds
Vertical: 100 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

Figure 14.- Induced voltage, a-c power bus 1, phase A (input mode: A + B).



Test pulse: 4000 amperes in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B



Test pulse: 8000 amperes in 2 microseconds
Vertical: 100 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

Figure 15.- Induced voltage, a-c power bus 2, phase A (input mode: A + B).

The leading edge of the simulated lightning current waveform shows a high-frequency current component superimposed on the exponential rise of the current waveform (fig. 16). This high-frequency component was caused by the lightning current generator trigger capacitor (200-picofarad) discharging into and ionizing the spark gap. The spark gap then discharged the main capacitor bank (6-microfarad) into the vehicle. Figure 17 shows the generator circuit involved. When the trigger capacitor discharged, rates of current change generated were 6 to 10 times higher than those caused by the main bank capacitor discharge. Equation 10 indicates the rate of current change upon initial discharge of the trigger capacitor charged to 225 000 volts.

$$(10) \quad \frac{dI}{dt} = \frac{E}{L} = \frac{225 \times 10^3}{5 \times 10^{-6}} = 45 \times 10^9 \text{ amperes/sec when } t = 0$$

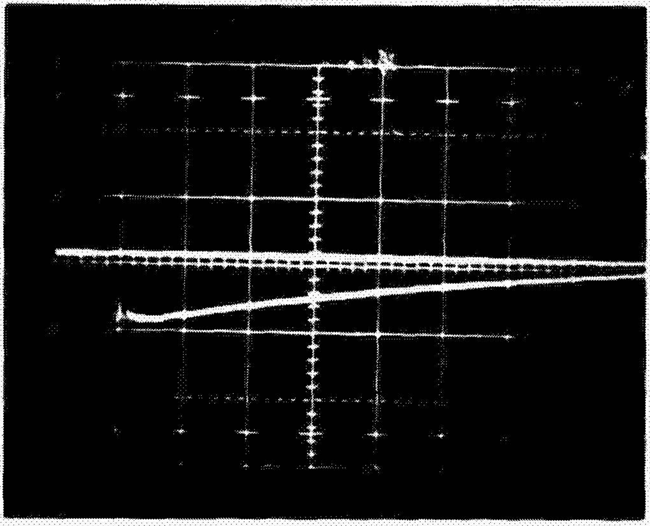
Equation 10 is valid when the trigger bank discharges into the estimated 5 microhenrys of the vehicle and the coaxial feed system. (The main capacitor bank internal inductance was estimated to be 3 microhenrys.) Although the trigger discharge energy content was more than three orders of magnitude below that of the main bank discharge, it contained more energy at the higher frequencies than the main discharge, and thus excited the spacecraft circuit high-frequency resonances.

Since the trigger capacitor was charged to the same voltage level for each stroke while the main capacitor bank was charged to 34 000 volts for the 4000-ampere stroke and 68 000 volts for the 8000-ampere stroke, the high-frequency energy spectrum remained constant while the low-frequency energy spectrum doubled between the 4000- and 8000-ampere strokes. This explains the nonlinearity observed when induced voltages that contained a significant portion of the energy at 1-megahertz and higher frequencies were scaled.

Scaling of induced voltages in this report includes the high frequency content. The scaled induced voltages shown could be reduced from 30 to 50 percent if the high frequency content of the induced voltage waveforms were excluded. Since information on the high-frequency spectral content of a natural or triggered lightning stroke is limited, the high-frequency response of circuits is included in the scaled voltages for conservatism.

4.2 Circuit Induced Voltages

Table VI summarizes the lightning induced voltages measured and scaled on spacecraft electrical circuits. All these measurements were taken at a 4000-ampere stroke level with a 2 microsecond rise time.



Test pulse: 4000 amperes in 2 microseconds
Vertical: 4000 amperes/division
Sweep speed: 5 microseconds/division

Figure 16.- Example of high-frequency simulated lightning current component.

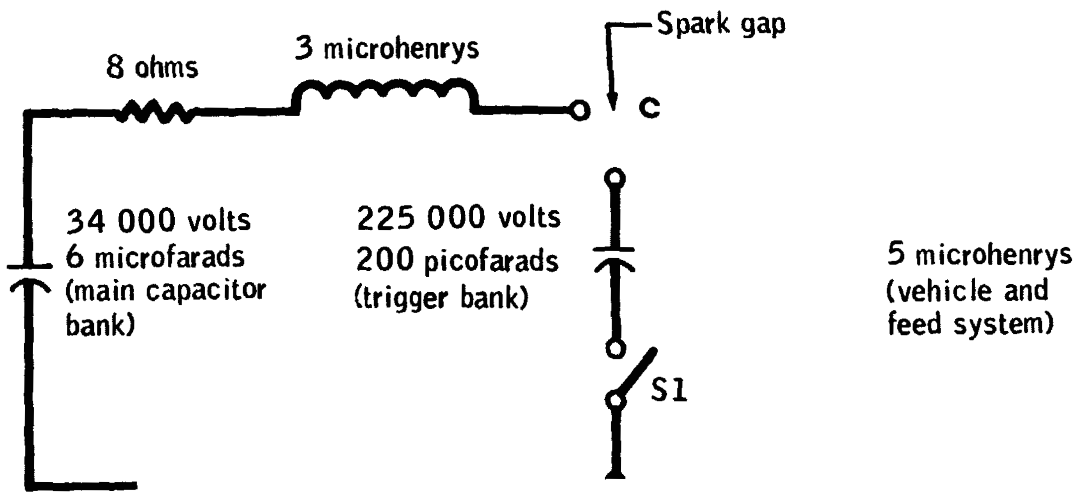


Figure 17.- Equivalent circuit of simulated lightning current path.

TABLE VI.- LIGHTNING INDUCED VOLTAGES MEASURED IN CSM 119 ELECTRICAL CIRCUITS[a]

Circuit	Lightning induced voltages					
	Measured at 4000 amperes (b)		Average stroke of 30 000 amperes (b)		Full-threat stroke of 200 000 amperes (b)	
	Line-line	Line-ground	Line-line	Line-ground	Line-line	Line-ground
Battery relay bus	9	24.5	67.5 (P)	184 (P)	450 (F)	1225 (P)
DC bus main A	40	50	300 (P)	375 (P)	2000 (F)	2500 (F)
DC bus main B	24	57	180 (P)	427 (P)	1200 (F)	2850 (F)
AC bus 1, phase A	48	81.5	360 (P)	610 (P)	2400 (F)	4070 (F)
AC bus 1, phase B	52	81	390 (P)	607 (P)	2600 (F)	4050 (F)
AC bus 1, phase C	30	107.5	225 (P)	805 (P)	1500 (F)	5375 (F)
AC bus 2, phase A	36	100.5	270 (P)	754 (P)	1800 (F)	5050 (F)
AC bus 2, phase B	44	99.5	330 (P)	746 (P)	2200 (F)	4990 (F)
AC bus 2, phase C	42	96	315 (P)	720 (P)	2100 (F)	4800 (F)
Yaw extend clutch output	12	41	90 (F)	307 (P)	600 (F)	2050 (F)
Roll gyro uncage relay driver	7	11	52.5 (P)	82.5 (P)	350 (F)	550 (P)
Ignition select no. 1	32	43.5	240 (F)	328 (P)	1600 (F)	2175 (F)
Reaction control system driver amplifier B1	17	23.5	127 (F)	176 (P)	850 (F)	1175 (P)
DC return to coupling data unit structure	30	30	225 (P)	225 (P)	1500 (F)	1500 (F)
[c]Master event sequence controller B	62	85.7	465 (P)	642 (P)	3100 (F)	3930 (F)
[c]Master event sequence controller A	82	109.5	615 (F)	811 (P)	4100 (F)	4800 (F)
Launch vehicle emergency detection system power (common mode)	180	180	1350 (F)	1350 (F)	9000 (F)	9000 (F)
S-IVB stage liquid oxygen tank A pressure	12	56	90 (P)	420 (P)	600 (P)	2800 (F)
Emergency detection system lift-off signal A	34	51.5	255 (P)	386 (P)	1700 (F)	2600 (F)
Emergency detection system abort 1	50	67.5	375 (P)	505 (P)	2500 (F)	3000 (F)
Emergency detection system abort 2	62	131	465 (P)	983 (P)	3100 (F)	6550 (F)
Emergency detection system abort 3	40	80	300 (P)	600 (P)	2000 (F)	4000 (F)
Spacecraft control pitch attitude error	1	NA	7.5 (P)	NA	50 (P)	NA

[a](P) indicates pass and (F) indicates fail.

[b]Time to peak was 2 microseconds in all cases.

[c]Service module jettison circuits.

Table VI also shows the induced voltage after linear scale-up to 30 000 amperes (average level) and 200 000 amperes (full-threat level), both with 2 microsecond rise times. A pass (P)/fail (F) notation follows each voltage entry in table VI for the 30 000- and 200 000-ampere levels. Pass/fail criteria are based on manufacturer steady-state component ratings and may be conservative for some of the short-duration transients observed; however, short-duration transient ratings are not generally available. A detailed discussion of each circuit and the potential failure mode is given in appendix B.

4.3 Pyrotechnic Test Results

The stray electrical energy indicator (SEEI) contains a 1-ohm fusible resistor in parallel with the 5-ohm bridgewire. A fired SEEI results in an increase in circuit resistance of about 200 milliohms.

Baseline pyrotechnic circuit resistance measurements were initially taken. Resistance measurements after the first test (4000 amperes in 2 microseconds) indicated that no SEEI's had fired. The next test (8000 amperes in 2 microseconds) fired SEEI's at three locations:

a. Tension tie detonator

b. Service module circuit interrupter

c. Pilot mortar 2

The pilot mortar SEEI was under the forward heat shield and was inaccessible. The other two fired SEEI's were replaced, and the test was repeated at the 8000-ampere level. No additional firings occurred.

The two accessible SEEI's were then replaced with battery-powered peak reading voltmeters. Subsequent testing produced peak voltages (pin-to-case mode) of 200 volts at the 4000-ampere stroke level and 320 volts at the 8000-ampere level. These results generally agree with line-to-ground voltage measurements made using the oscilloscopes since the 200-volt measurement scales to a full-threat level (50 x 200 volts) of 10 000 volts. Some of the 78 units installed would have a minimum firing voltage below that indicated by the six units fired during sensitivity testing prior to shipment (table III). Therefore, the firing of the three SEEI's at a 320-volt pin-to-case level could be expected. The pyrotechnic portion of the test was terminated without testing at the 12 000-ampere level because additional margin could not be demonstrated.

SEEI results show a +2.4 decibel safety margin for 75 of the 78 test spacecraft pyrotechnic circuits. Induced voltage measurements on two of the remaining three circuits gave a +6 decibel safety margin for full-threat lightning. The wire routing for the inaccessible pyrotechnic circuit would not subject it to higher induced voltages than the other pyrotechnic circuits. Therefore, all of the test vehicle pyrotechnic circuits have at least a +2.4 decibel margin of safety for full-threat lightning.

4.4 Field Coil Measurement Results

The two measurement coils located in the command module tunnel yielded 969 volts per square meter of loop area for the +Y axis location and 1292 volts per square meter for the -Y axis location when the results were scaled up to a full-threat stroke of 200 000 amperes with a 2 microsecond rise time. The Thevenin equivalent circuit source impedance (open-circuit voltage divided by short-circuit current) was less than 1 ohm. This result confirmed previous test results and indicated that the source impedance associated with lightning induced voltages can be neglected for the purposes of circuit analysis.

4.5 Duplication of Apollo 12 Lightning Induced Equipment Disturbances

The Apollo 12 space vehicle was struck by lightning twice during the launch phase (ref. 1). The lightning strikes caused a number of equipment operation upsets, and some equipment failures. The test spacecraft also experienced equipment operation upsets as a result of the applied 4000-ampere current pulse. The following is a list of upsets experienced by both the test spacecraft and the Apollo 12 spacecraft.

a. Fuel cells disconnected.

b. Coupling data unit counter bits were set.

c. Central timing equipment reset to zero.

d. Master alarm came on.

e. DC bus undervoltage warning lights came on.

f. Signal conditioner equipment had a momentary dropout.

The following is a list of Apollo 12 upsets and failures that did not occur during the testing:

a. AC bus 1 undervoltage fail light came on.

b. AC 1 and 2 overload lights came on.

c. The inertial measuring unit lost reference. (As a result of the Apollo 12 problem, the command module computer program was modified to prevent recurrence of this problem, precluding the situation.)

d. The reaction control system propellant quantity measurement transducers failed. (These were disconnected for the tests.)

e. Four service module outer surface temperature measurement transducers failed. (These were not installed.)

From the preceding comparison and the data summarized in table VI, the Apollo 12 lightning stroke had a current rate of rise in the range from 2000 to 15 000 amperes per microsecond.

5.0 CONCLUSIONS

5.1 General

a. Test waveform - Some authorities have promoted the use of a damped sine wave instead of the damped exponential waveform used in this type of test. Oscillograms of induced voltage indicate that circuit resonance is an important factor in circuit peak response. Therefore, the damped exponential waveform which contains the spectral distribution of a natural lightning stroke is necessary to excite circuit resonances rather than the limited frequency content of a damped sine wave.

b. Simulated lightning test level - The test levels were chosen to confirm the validity of linear scaling, verify pyrotechnic margins using existing sensitive simulators, and prevent damage to the spacecraft. The ratio of the sensitivity of the pyrotechnic initiator simulator to that of the flight pyrotechnic initiator was the prime factor in selecting test levels. Test levels an order of magnitude lower could have been used if circuit responses had been measured instead of using go/no-go detectors such as the pyrotechnic simulators. A reduced test level should be considered for future testing to simplify the test configuration and simulated lightning generation equipment.

c. Measurement technique - Obtaining photographs of oscilloscope traces (oscillograms) was the prime method of data collection. This technique is necessary for any measurement in which an active component can change state or operate through a voltage range as a result of an induced transient. Peak-reading voltmeters can be used when monitoring circuits with passive components. If peak-reading voltmeters were used on active circuits, the resulting reading would be a combination of induced voltage and component change-of-state voltage. Only the induced voltage can be scaled. The two components can be separated using an oscillogram. Peak-reading voltmeters, if used, should have a charging time constant of less than 10 nanoseconds.

d. Linear scaling - The validity of scaling induced voltages was demonstrated with sufficient rigor to justify the conclusions reached in this report; however, the high-frequency spectral content of the test waveform did not double as the test level was doubled because of the method used to trigger the discharge of the main capacitor bank. The induced voltages scaled to average and full-threat levels were from 30 to 50 percent high because of the trigger circuit ringing.

5.2 Specific

a. The highest induced voltages were measured in the wiring which was routed close to the main lightning current paths.

b. Many of the power and signal critical circuits would fail it subjected to full-threat (200 000-ampere) lightning. Power and signal circuits are marginal for an average lightning stroke of 30 000 amperes.

c. Pyrotechnic circuits are safe for full-threat lightning. The test demonstrated a safety margin of at least +2.4 decibels for the test spacecraft. This, however, was based on an assumed all-fire level of 25 000 volts for the SBASI and, as discussed in paragraph 3.3, the true all-fire level is probably much higher.

d. Common-mode (line-to-ground) voltages were higher than expected and exceeded the failure criteria level for all but three of the circuits tested. Circuit failures at the full-threat level were predicted on such a high percentage of the circuits investigated that design corrections to improve survivability are not practical.

6.0 REFERENCES

1. Apollo 12 Mission Report. NASA Johnson Space Center Report MSC-01855, March 1970, pp. 14-2 through 14-7.

2. Tantalum Capacitor Behavior Under Fast Transient Voltage Pulses. NASA TM X-58152, to be pub. Dec. 2, 1974.

APPENDIX A - STRAY ELECTRICAL ENERGY INDICATOR

The SEEI initiator is identical to the single bridgewire Apollo standard initiator (SBASI) shown in figure A-1 with the following exceptions:

1. The bridgewire is Tophet* alloy instead of Nilstain* alloy. The resultant bridgewire resistance is 4.5 ±0.7 ohms instead of 1.05 ±0.1 ohms.

2. The ceramic charge cup is silver plated (except in the area of the bridgewire) to provide an electrical path to the body.

3. The bridgewire is thermally isolated from the ceramic charge cup by H-film.

4. The bridgewire is slurried with lead styphnate instead of Space Ordnance Systems* (SOS) no. 108 mix.

5. The SOS no. 108 explosive charge that is pressed over the lead styphnate is bound with varnish instead of Viton-B.*

6. The SEEI initiator is mounted in a housing with an internal extendable bellows. Initiation causes extension of the bellows past a viewing hole in the housing to confirm activation.

*Trade names.

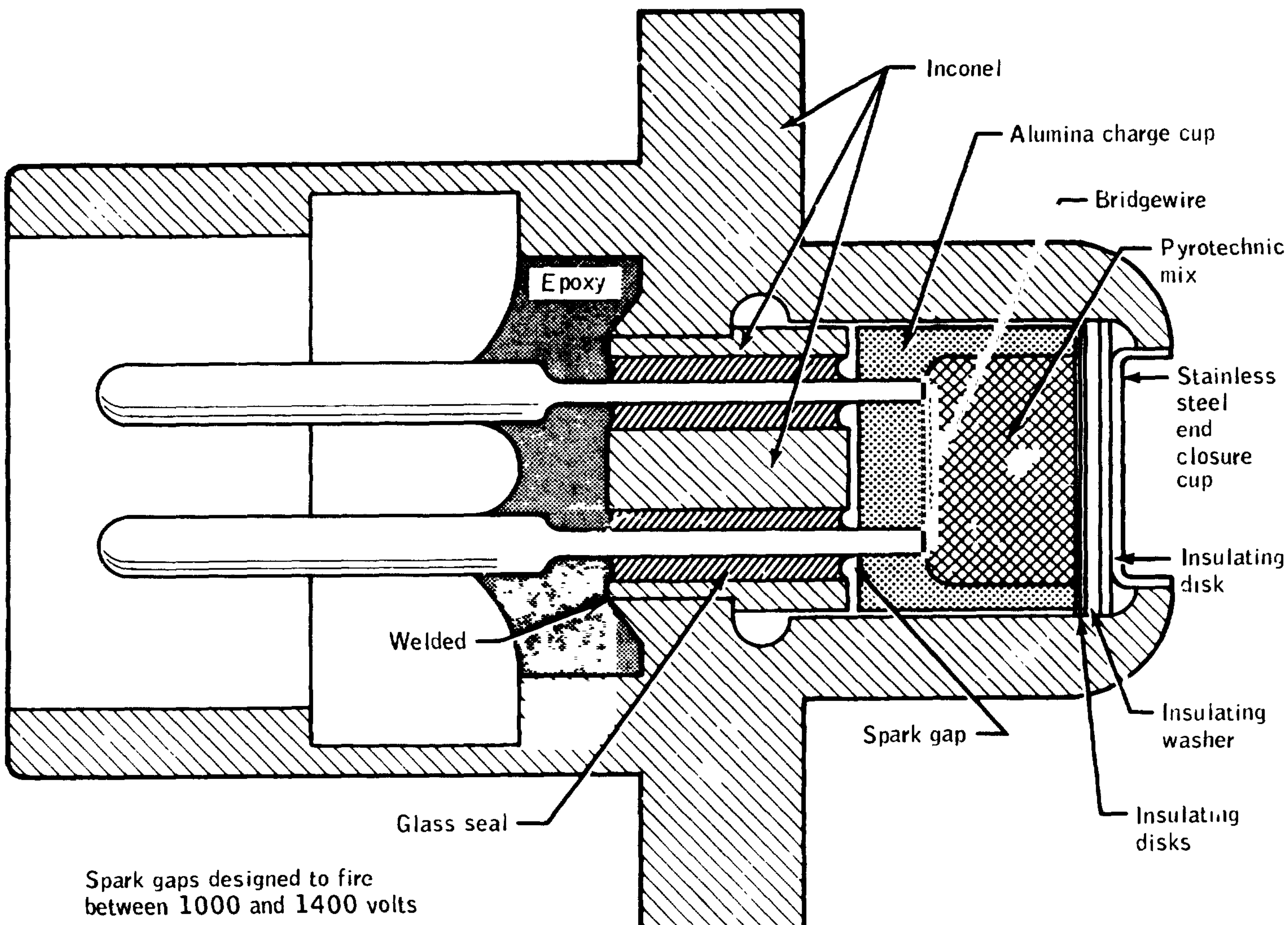


Figure A-1.- Single bridgewire Apollo standard initiator.

APPENDIX B - INDUCED VOLTAGE CIRCUIT EFFECTS

This appendix contains a discussion of the circuit effects of the voltages measured when scaled to full lightning levels. A simplified schematic of each circuit type monitored is given, as well as oscillograms of the differential and common-mode voltages measured during the test. The voltages quoted are scaled to a 200 000-ampere-peak (full-threat) lightning stroke and a 30 000-ampere-peak (average) lightning stroke, both with 2-microsecond rise times. Scaling was done by multiplying measured voltages by 50 for full-threat and by 7.5 for average lightning. All measured and scaled voltages are given in table VI.

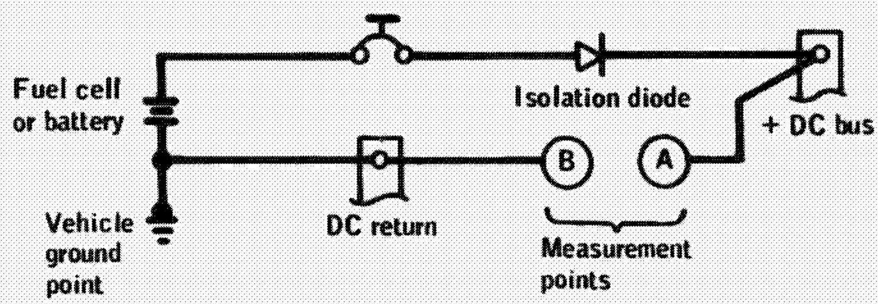
The discussions of circuit effects are based on manufacturer's component maximum d-c ratings. This gives conservative results in many cases since most electronic components can survive short-duration transient voltages much higher than the maximum d-c ratings. For example, testing has shown that dry and wet tantalum capacitors will not fail when subjected to voltage transients shorter than 25 microseconds duration (ref. 2).

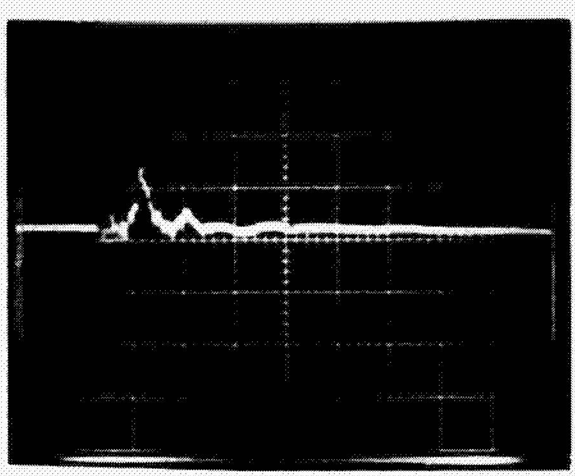
B.1 Battery Relay Bus and Direct Current Buses

The measured differential and common-mode voltages for direct-current bus main A scaled to full-threat level were 2000 and 2500 volts, respectively. Direct current bus main B showed a higher common-mode voltage (2850 volts). The battery relay bus showed lower differential and common-mode voltages than either direct-current buses main A or B.

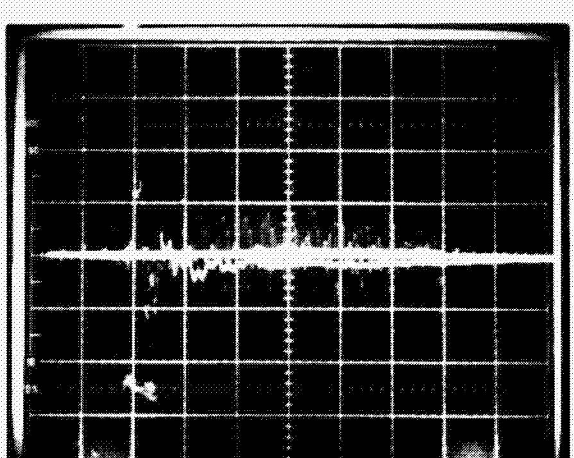
The batteries and fuel cells have very low internal impedances and many equipments that use d-c power from the buses have input filter capacitors that appear as short circuits to the lightning induced voltages. As a result, the high negative differential voltage would appear across the current isolation diodes (fig. B-1) exceeding the reverse voltage ratings (400 to 600 volts) and causing the diodes to short. A shorted isolation diode would allow the associated fuel cell or battery to take reverse current from the bus if the bus voltage was higher than the fuel cell or battery terminal voltage.

The high common-mode voltage induced by a full-threat lightning stroke could cause arc-over in the wiring, coupling the high voltage into the isolation diodes with the results noted above. An average lightning stroke would give differential and common-mode voltages of 300 and 427 volts, respectively, which should not cause component damage.





Test pulse: 4000 amperes
in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



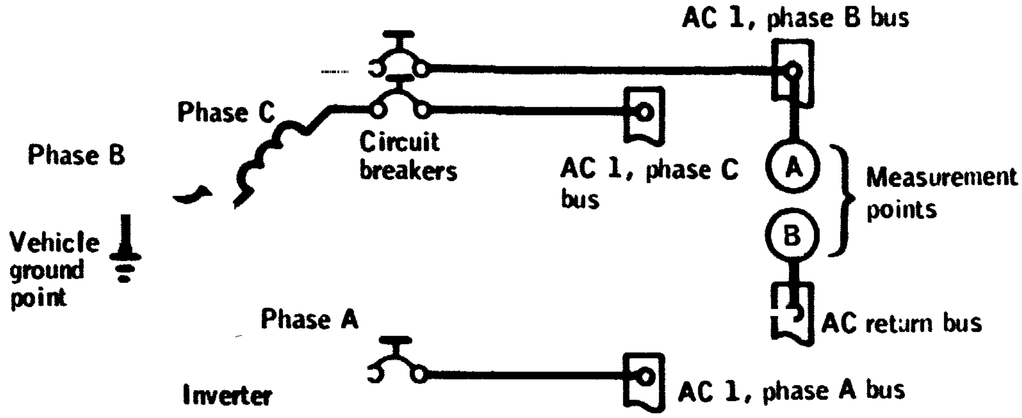
Test pulse: 4000 amperes
in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

Figure B-1.- DC bus main A.

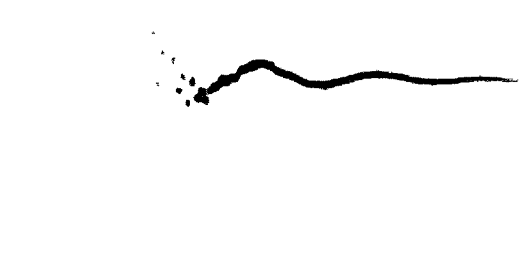
B.2 Alternating Current Buses

Differential and common-mode voltages for alternating-current bus 1 phase B (fig. B-2) for the full-threat level were 2600 and 4050 volts, respectively. The differential voltage was the highest experienced by all three phases of both buses. Alternating-current bus 1 phase C showed the highest common-mode voltage (5375 volts). The 4050 volts common-mode would be expected to arc through wire insulation. If an insulation char path was created due to common mode, the arcing would continue because the inverter is a low-impedance high-current source. Ultimately, the associated alternating-current phase circuit breakers would open. The arcing could also short turns in the motors or transformer windings, and lead to component failures.

The differential and common-mode voltages resulting from an average lightning stroke would be 390 and 805 volts, respectively, which should not cause arc-over.



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 50 volts
Sweep speed: 2 microseconds/division
Measurement mode: A + B

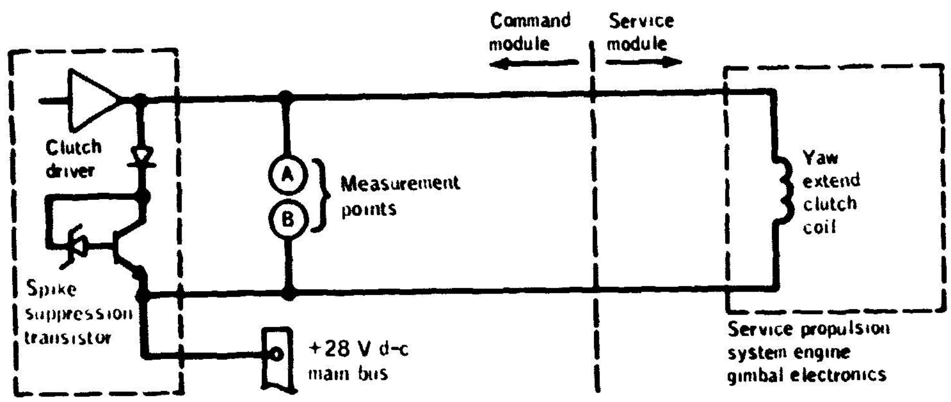
Figure B-2.- AC bus 1, phase B.

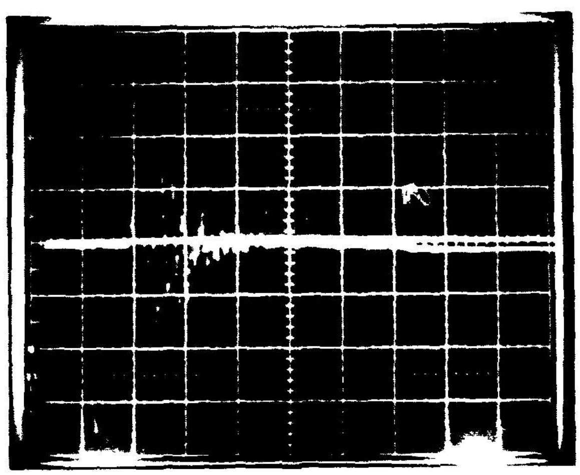
B.3 Yaw Extend Clutch Output

The full-threat differential and common-mode voltages were 600 and 2050 volts, respectively. The differential voltage is sufficient to short the spike suppression transistor collector, which is rated at 40 volts. The yaw extend clutch coil would then be bypassed by a short circuit. Subsequent operation of the clutch driver shown in figure B-3 could result in the driver shorting since the driver output current would no longer be limited by the extend clutch coil resistance.

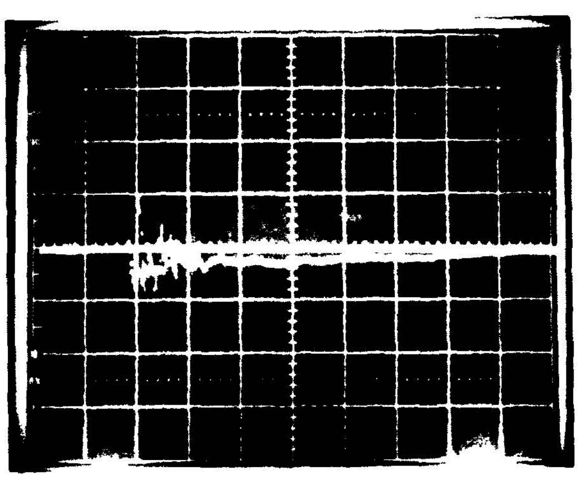
The high common-mode voltage could arc over the wiring, shifting the high common-mode voltage to the spike suppression network and, again, causing transistor failure.

The corresponding differential and common-mode voltages for an average lightning stroke are 90 volts (which exceeds the spike supression transistor rating) and 307 volts, respectively.





Test pulse: 4000 amperes
in 2 microseconds
Vertical: 10 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

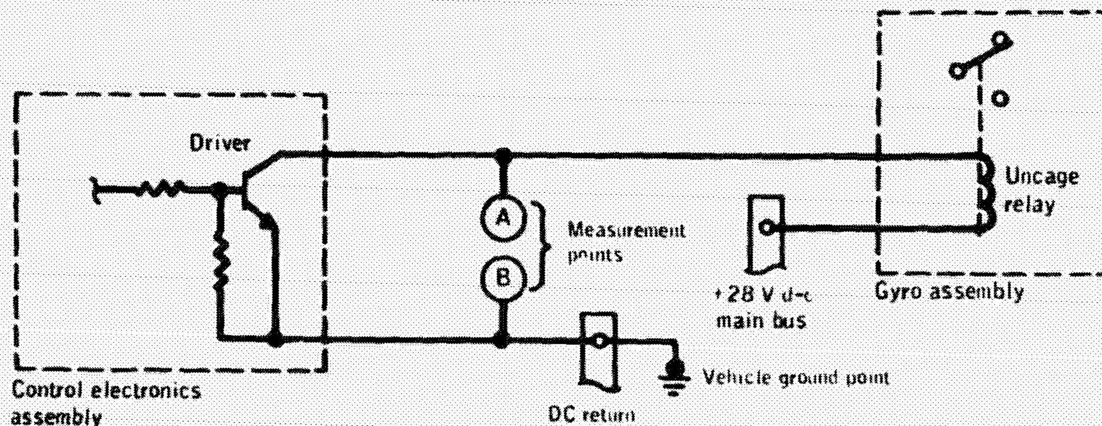
Figure B-3.- Yaw extend cluch output.

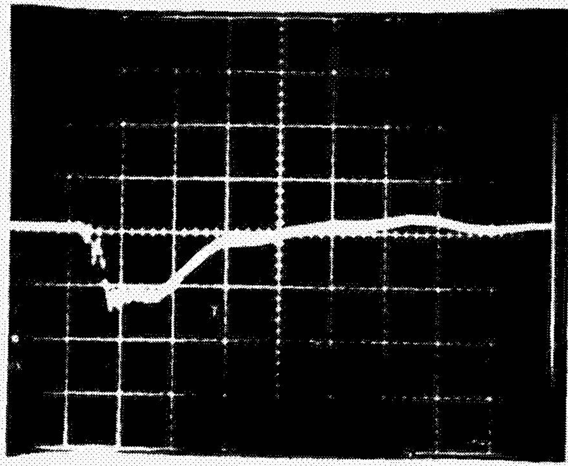
B.4 Roll Gyro Uncage Relay Driver

About 1 microsecond after the test pulse was applied, the relay driver (fig. B-4) turned on, as shown by the 24-volt decrease in the minus B oscillogram. This most likely was caused by induced voltage being coupled into the driver circuit upstream of the driver transistor since only 14 volts peak was induced in the driver output line, which is insufficient to cause turn-on.

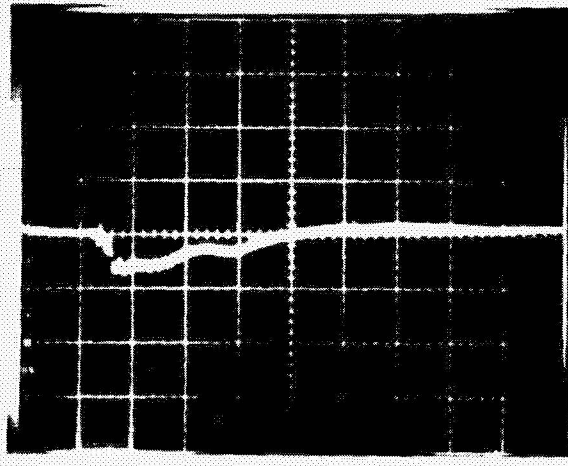
The full-threat differential and common-mode voltages were 350 and 550 volts, respectively. The 350 volts differential is sufficient to break down the transistor collector (rated at 80 volts) and could cause the transistor to short. The 550 volts common-mode is not high enough to cause arc-over in the wiring.

The differential and common-mode voltages resulting from an average lightning stroke were 52 and 82 volts, respectively. The 52 volts differential added to the 28 volts spacecraft power normally applied to the transistor collector gives 80 volts, insufficient to break down the transistor collector.





Test pulse: 4000 amperes
in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

Figure B-4.- Roll gyro uncage relay driver.

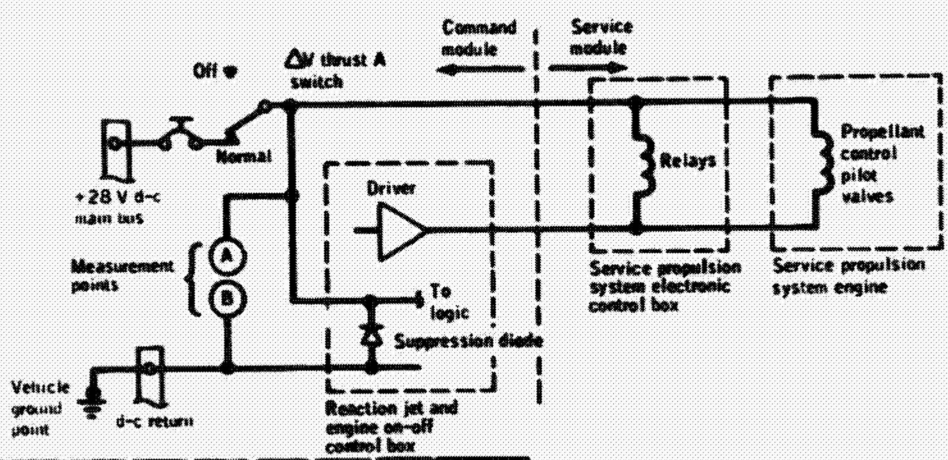
B.5 Ignition Select No. 1

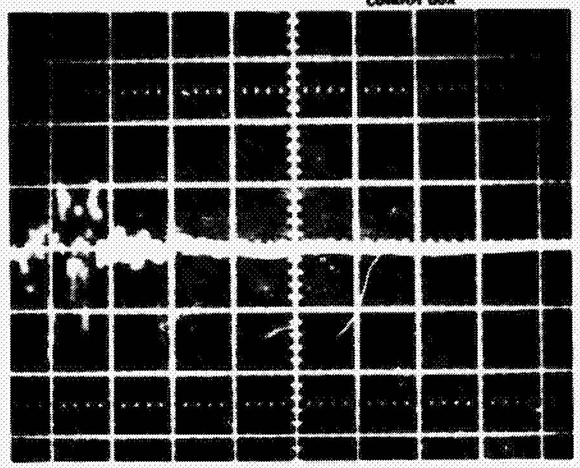
The differential and common-mode voltages resulting from a full-threat stroke were 1600 and 2175 volts, respectively. The suppression diode shown in figure B-5 has a reverse voltage rating of 600 volts. The 1600 volts is sufficient to short the suppression diode since the only other components in the induction loop (that will limit current through the suppression diode) are the battery and one or more forward biased steering diodes in the power distribution system (not shown).

If the suppression diode shorted, the circuit breaker that supplies the reaction control system reaction jet and engine on-off control logic and the service propulsion system engine propellant pilot valves would open. Since the identical redundant circuit is subject to the same failure, the service propulsion system would be unusable.

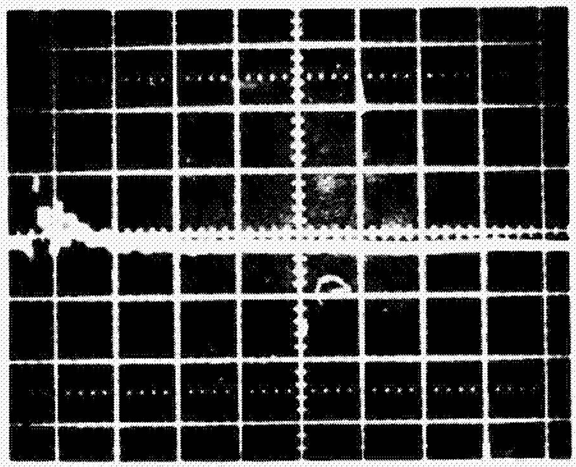
The common-mode voltage (2175 volts) could arc over the wiring, coupling the high voltage into the reaction control system jet and engine on-off control logic components.

An average lightning stroke would induce 240 volts differential, and 328 volts common mode. The common-mode voltage should be acceptable but the differential voltage may be sufficient to damage logic components.





Test pulse: 4000 amperes
in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

Figure B-5.- Ignitation select no. 1.

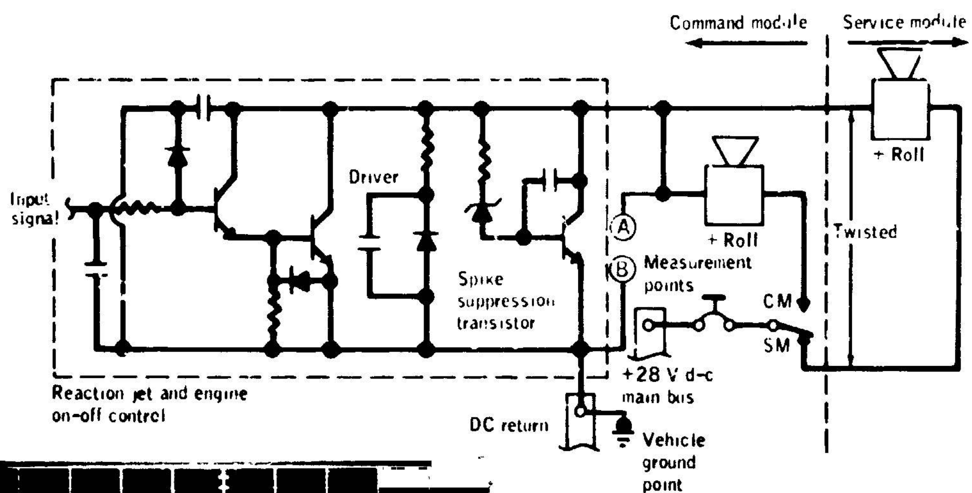
B.6 Reaction Control System Driver Amplifier B1

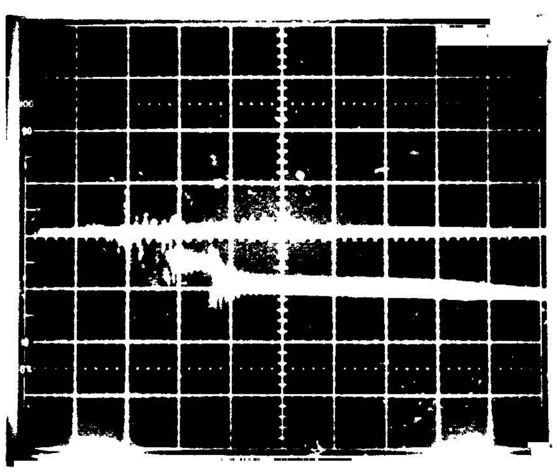
The measured differential voltage (fig. B-6) stepped down 10 volts at 2 to 3 microseconds after the start of the test pulse. Two microseconds later, the voltage decreased another 10 volts. Each decrease was accompanied by a damped oscillation burst.

The first voltage decrease was probably caused by the spike suppression transistor (fig. B-6) turning on. This turn-on would result from the driver output line induced voltage charging the capacitor that is connected between the suppression transistor collector and base. The spike suppression transistor turn-on would then draw current through the valve coil and the coil would ring, giving the damped oscillation burst.

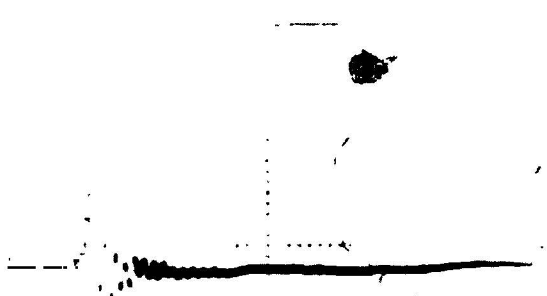
The second voltage decrease could have resulted from induced voltage charging the capacitor that is connected between the driver input transistor base and ground. This would turn on the driver and the increased current through the engine valve coil would give another burst of inductive ringing.

The differential voltage before turn-on of the spike suppression transistor scales up to 850 volts for a full-threat stroke. The scaled common-mode voltage is 1175 volts. The differential level of 850 volts exceeds the driver transistor maximum collector rating by 790 volts and could cause the transistor to short. The corresponding differential voltage for an average stroke is 127 volts, exceeding the transistor maximum collector voltage (60 volts). The common-mode voltage for a full-threat or average lightning stroke is not high enough to exceed wire insulation ratings.





Test pulse: 4000 amperes
in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

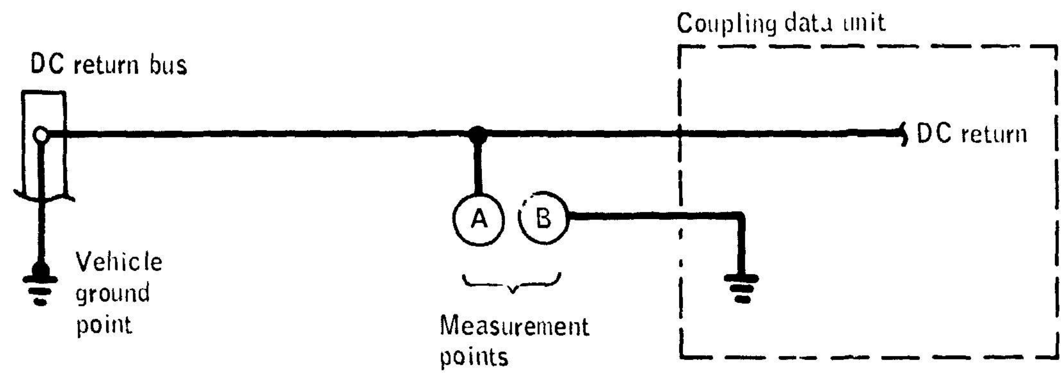
Figure B-6.- Reaction control system driver amplifier B1.

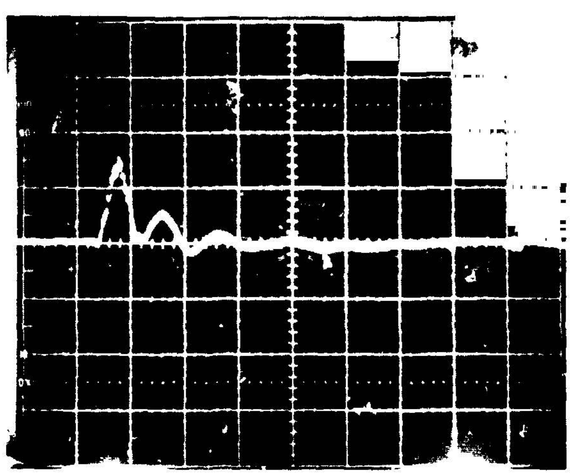
B.7 Direct Current Return to Coupling Data Unit Structure

The full-threat differential and the common-mode voltages were both 1500 volts, as expected, since one of the measurement points was structure (fig. B-7). The fact that the two voltages were the same validated the method used to measure the voltages.

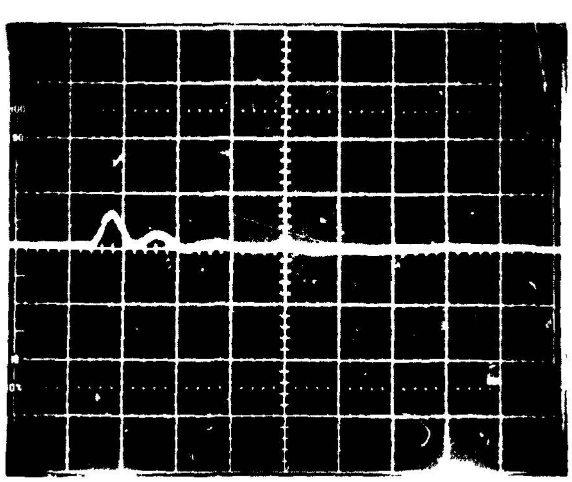
The common-mode voltage is sufficient to arc through the insulation of the wiring inside the coupling data unit. Such arcing could establish a second ground point in the coupling data unit and couple ground loop voltages into the unit during subsequent operation. This could result in improper coupling data unit operation.

The average lightning stroke induced common-mode voltage was 225 volts, which is safe.





Test pulse: 4000 amperes
in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurements mode: A + B

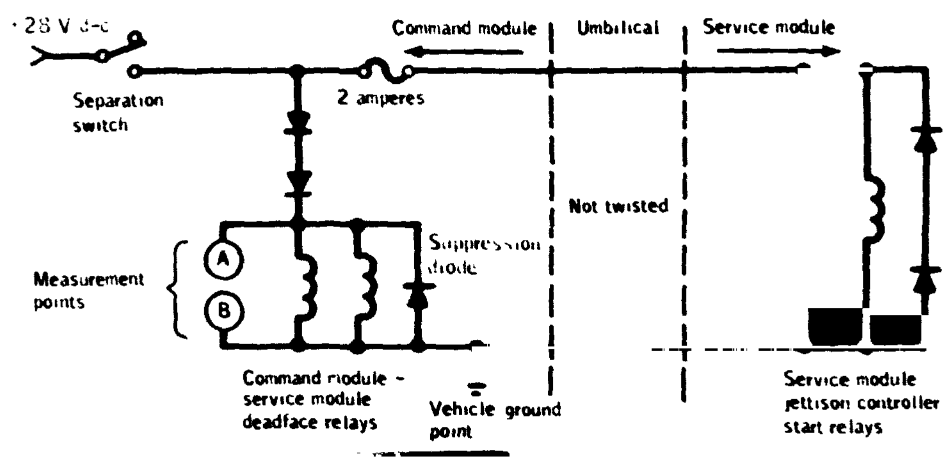
Figure B-7 DC return to coupling data unit structure.

B.8 Service Module Jettison Circuits

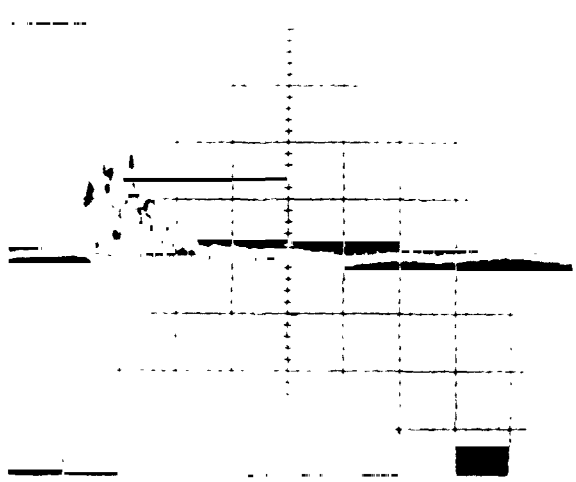
The full-threat induced differential voltage of 4100 volts is enough to short the command module/service module deadface relay suppression diode (fig. B-8). With this diode shorted, subsequent operation of the separation switch would result in a thermal-race-to-burn-open between this diode and the two series diodes feeding the deadface relay coils. If one of the two series diodes burned open first, the deadface relays could not be energized.

A full-threat scaled common-mode voltage of 4800 volts would arc from wiring to structure. The common-mode voltage then would couple into and short the diodes.

The differential and common-mode voltages resulting from an average lightning stroke are 615 volts and 811 volts, respectively. This differential voltage exceeds the 600-volt rating of the relay suppression diode. The common-mode voltage is safe.



Test pulse: 4000 amperes in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurement mode. A + B

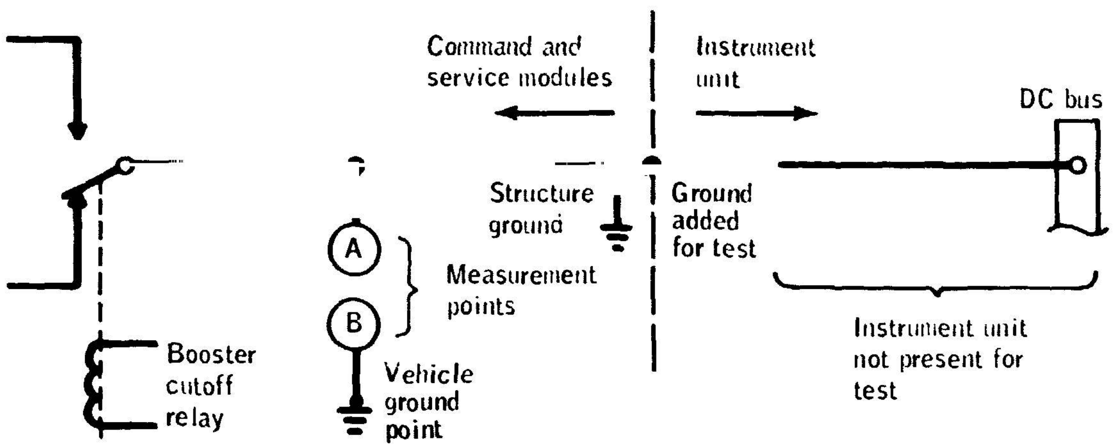
Figure B-8.- Service module jettision circuit.

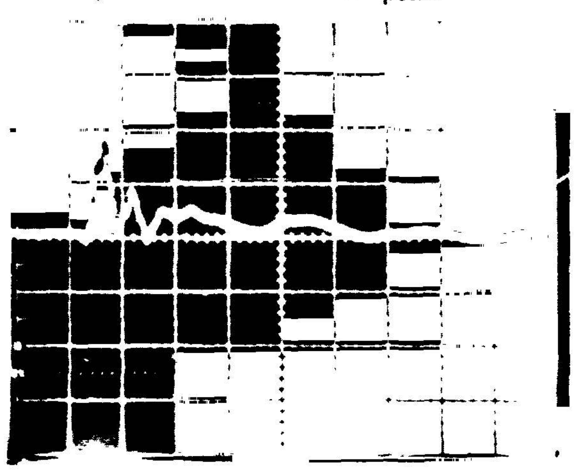
B.9 Launch Vehicle Emergency Detection System Power

The circuit (fig. B-9) was deliberately grounded at the spacecraft/launch vehicle adapter interface connector to transfer the full common-mode voltage to the measurement points in the cabin. Measured common-mode and differential voltages were, therefore, equal.

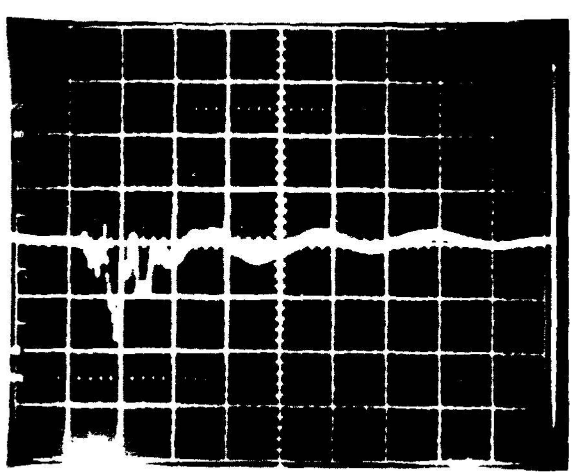
The full-threat induced common-mode voltage of 9000 volts would cause harness and connector arc-over to structure.

The average induced common-mode voltage of 1350 volts exceeds the 1000-volt rating of miniature connectors used inside electronic packages.





Test pulse: 4000 amperes
in 2 microseconds
Vertical: 100 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 100 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

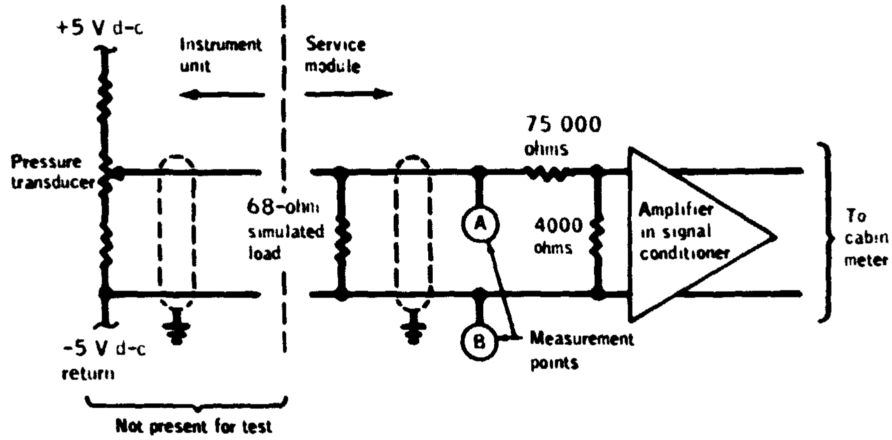
Figure B-9.- Emergency detection system power bus.

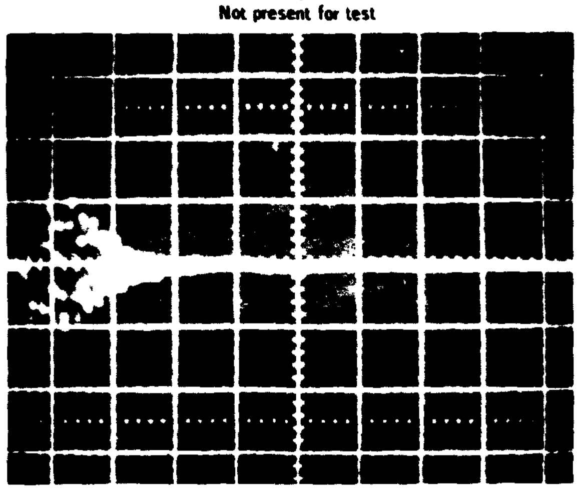
B.10 Launch Vehicle S-IVB Stage Liquid Oxygen Tank A Pressure

The full-threat induced differential voltage was 600 volts and is insufficient to damage any of the circuit components (fig. B-10).

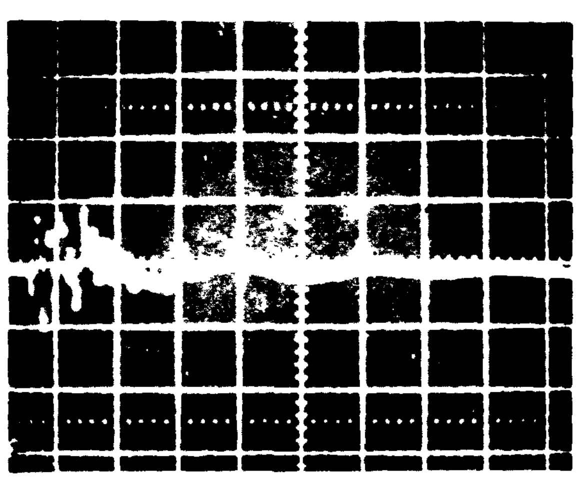
The full-threat induced common-mode voltage was 2800 volts, which would arc over from wire to structure. Arc-over would establish a second circuit ground point and transfer the common-mode voltage to circuit components. Component damage could then be expected to occur.

The average lightning induced common-mode and differential voltages were 420 and 90 volts, respectively, which are safe.





Test pulse: 4000 amperes in 2 microseconds
Vertical: 10 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



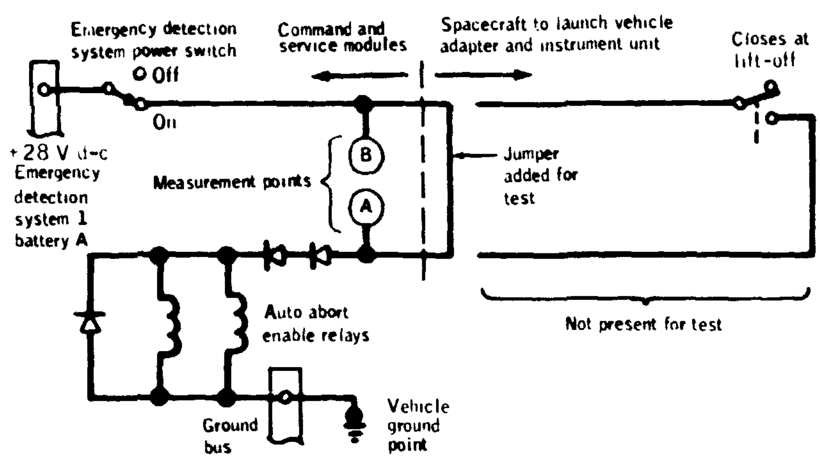
Test pulse: 4000 amperes in 2 microseconds
Vertical: 50 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

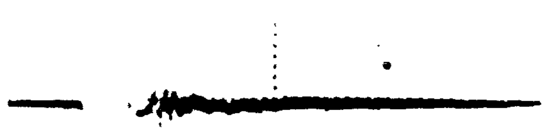
Figure B-10.- Launch vehicle S-IVB stage liquid oxygen tank A pressure measurement.

B.11 Emergency Detection System Lift-Off Signal A

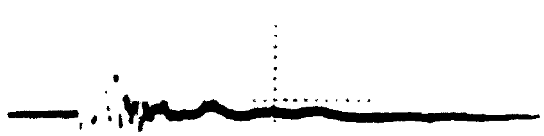
The full-threat induced differential and common-mode voltages were 1700 volts and 2600 volts, respectively. The 1700 volts could short the automatic abort enable relay suppression diode (rated at 600 volts) shown in figure B-11, preventing subsequent operation of the relays. The common-mode voltage could cause arc-over in the wiring and connectors.

The corresponding differential and common-mode voltages from an average lightning stroke are 225 and 386 volts, respectively. These are safe.





Test pulse: 4000 amperes
in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes
in 2 microseconds
Vertical: 100 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

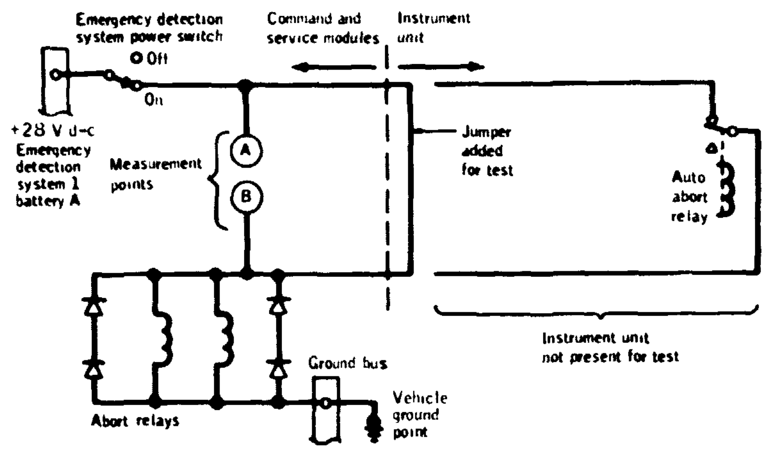
Figure B-11.- Emergency detection system lift-off signal A.

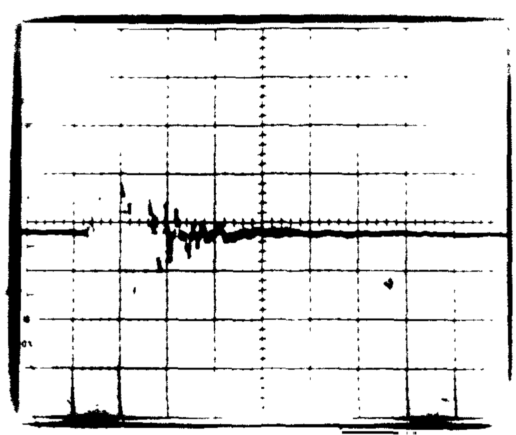
B.12 Emergency Detection System Automatic Abort Command

The differential voltage for full-threat lightning was 3100 volts. This could arc over the automatic abort relay contacts in the instrument unit (fig. B-12). The differential voltage would then be shifted to the emergency detection system abort relay suppression diodes, causing them to short. Shorted suppression diodes would prevent subsequent operation of the abort relays.

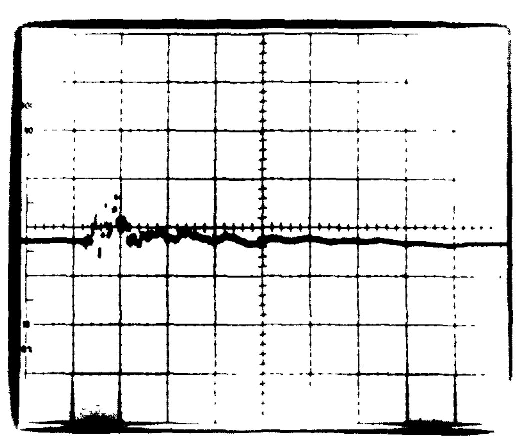
The full-threat common-mode voltage of 6550 volts would cause arc-over in the wiring and connectors.

An average lightning stroke would induce differential and common-mode voltages of 465 and 983 volts, respectively. These voltages would not be expected to cause hardware damage in the automatic abort command circuits.





Test pulse: 4000 amperes in 2 microseconds
Vertical: 20 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B



Test pulse: 4000 amperes in 2 microseconds
Vertical: 100 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A + B

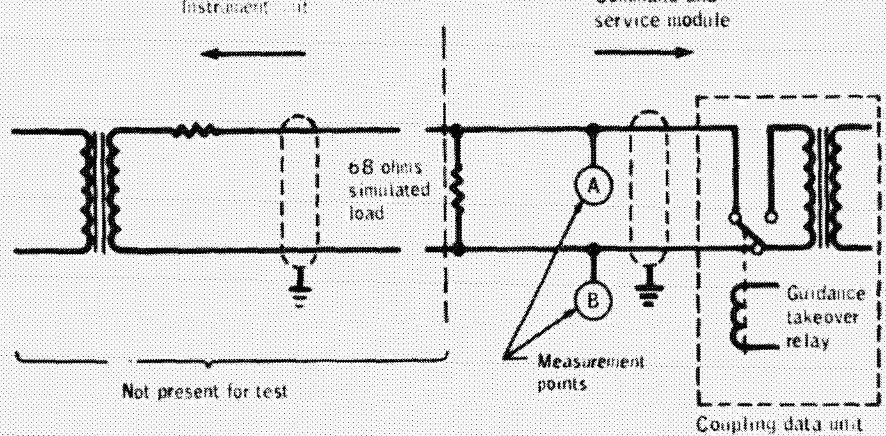
Figure B-12.- Emergency detection system automatic abort command relay.

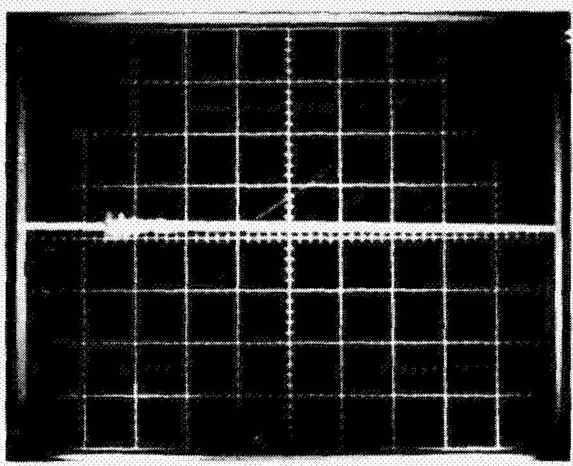
B.13 Spacecraft Control Pitch Attitude Error

The differential voltage at full-threat level was 50 volts. This is insufficient to cause any problem since the winding-to-winding insulation ratings of the instrument unit transformer and the coupling data unit transformer (fig. B-13) are 1000 volts.

No valid common-mode voltage measurement was made because the oscilloscope used to make the measurements established the only structure ground in the system. The launch vehicle emergency detection system power common-mode measurement (sec. B.9) is representative of the common-mode voltage that could be expected in the pitch attitude error circuit. That measurement scaled to 9000 volts, sufficient to arc over in the wiring and rupture the interwinding insulation in both transformers in the pitch attitude error circuit.

Differential and common-mode voltages for an average lightning stroke are 7.5 and 1350 volts, respectively, and should be safe.





Test pulse: 4000 amperes in 2 microseconds
Vertical: 5 volts/division
Sweep speed: 2 microseconds/division
Measurement mode: A - B

Figure B-13.- Spacecraft control pitch attitude error.